

Long-term, consistent scenarios of emissions, deposition, and climate change in Europe

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Abstract

The aim of this study was to develop consistent scenarios of emissions, climate change and regional air pollution to enable an integrated analysis of the linkage between climate change and regional air pollution in Europe. An integrated modeling framework was developed for this purpose. The framework integrates state-of-the-art models and concepts from the area of climate change and regional air pollution and was supplemented by new modules (e.g. modeling long-term NH₃ emissions in Europe, modeling dispersion and transformation of air pollutants under climate change).

Consistent climate and air pollution policies were derived, both driven by the desire to achieve certain environmental goals. According to an analysis of scenarios with various combinations of climate and regional air pollution policies the quantitatively most relevant interactions are the effect of climate change policies on the energy mix and the resulting air pollution emissions. In the long-term the global SO₂ emissions are expected to decrease (again), accordingly their effect on climate will be minor. Tentatively it can be concluded that for regional air pollution the development of the air pollutant emissions is more important than the effect of climate change on the dispersion and chemical transformation of air pollutants.

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1. Introduction

Among the many challenges facing Europe as a community are the environmental problems that transcend its borders, among them regional air pollution and climate change. There are important overlaps between these issues from the perspective of both science and policy:

- Climate change may alter the environmental impacts of air pollutant emissions. Climate change, for example, is likely to alter European weather patterns, and this will affect the distribution of air pollutants throughout Europe.
- SO₂ emissions have a cooling effect and thus may counteract climate change caused by greenhouse gas emissions.

- The causes of greenhouse gas emissions and air pollutant emissions are linked in the European economy. For example, changes in the amount and types of fuels that are consumed will affect the rate of emissions of both air pollutants and greenhouse gas emissions. Policies to reduce air pollutant emissions, such as switching from high-sulfur coal to low-sulfur natural gas, will also reduce the emissions of some greenhouse gases.

For both regional air pollution and climate change, coherent European policies have evolved. European policymakers, however, have handled the two environmental problems separately up to now. One reason for this separate approach has been that policymakers do not have the quantitative information needed to develop policies that address both regional air pollution and climate change in Europe.

The aim of this study was to develop consistent scenarios of emissions, climate change and regional air pollution to enable an integrated analysis of the linkage between the two problems in Europe (see [Alcamo et al., 2002](#)).

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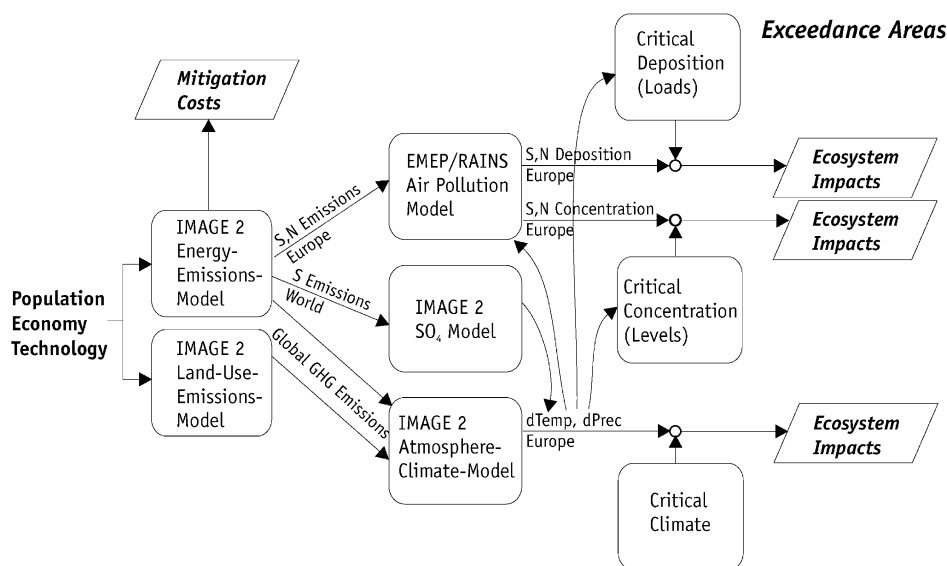


Fig. 1. Integrated modeling framework of AIR-CLIM.

2. Methodology

2.1. The integrated modeling framework

An integrated modeling framework is used to meet the objectives of the AIR-CLIM project (Fig. 1). The expression ‘framework’ is more appropriate than model because many of its components are not electronically ‘hard’ linked, i.e. they are not components of the same computer programs. In some cases output from one component has to be processed externally before used as input to the next component. The framework consists of the integrated model of climate change IMAGE (Sections 2.2 and 2.3) and of some parts of the integrated model RAINS covering regional air pollution in Europe (Alcamo et al., 1990; Amann et al., 1995). RAINS combines a variety of information relevant for the development of cost-effective emission control strategies in Europe. For that it describes the pathways of emissions of sulfur dioxide, nitrogen oxides and ammonia and explores their impacts on regional air pollution. The parts of RAINS relevant for this paper are the use of so-called source-receptor matrices to link air pollutant emissions to air pollution deposition and concentrations (Section 2.5).

In addition to the existing models, the framework is supplemented by new components. The new components relevant for this paper are: (1) a module to calculate the ammonia emissions in Europe after 2010 (Section 2.4), and (2) an extension of the source-receptor matrices for air pollution deposition and concentrations so that they take climate change in the atmosphere into account (Section 2.5.2).

In this paper, the AIR-CLIM scenarios of emissions, climate change and European air pollution are presented and the respective models accordingly introduced. The critical thresholds and their exceedances as well as the calculation

of mitigation costs are described in the other papers of this special issue (Guardans, 2002; Posch, 2002; van Harmelen et al., 2001; van Minnen et al., 2001). Alcamo et al. (2002) give an overview of the whole integrated modeling framework and present an overview of the results of the whole AIR-CLIM project.

2.2. Modeling global environmental change: IMAGE 2.1

The IMAGE 2.1 model is an integrated global change model that provides comprehensive quantitative and geographically-detailed information about trends in greenhouse gas emissions and their impact on climate, the biosphere, and society (Alcamo, 1994; Alcamo et al., 1998a).

The driving forces are changes in population, economy, and technology. Based on assumptions about these driving forces, IMAGE 2.1 computes future changes in the consumption of energy, food, and timber. This consumption leads to greenhouse gas emissions from energy and industry, shifts in land use and land cover, and changes in the fluxes of gases from the terrestrial environment. The emissions and fluxes of gases lead to changes in the atmospheric composition of various gases, as well as changes in the flux of heat and moisture between the terrestrial, oceanic and atmospheric environments. Eventually these fluxes affect regional climate, and these changes in regional climate feed back to the terrestrial and oceanic environments in different ways, for example, by changing the productivity of crops and the required amount of future agricultural land.

The model is constructed from 13 individual global submodels organized into three fully linked subsystems: Energy-Industry, Terrestrial Environment, and Atmosphere-Ocean (see Fig. 2). The *Energy-Industry* models compute the emissions of greenhouse and other gases from five

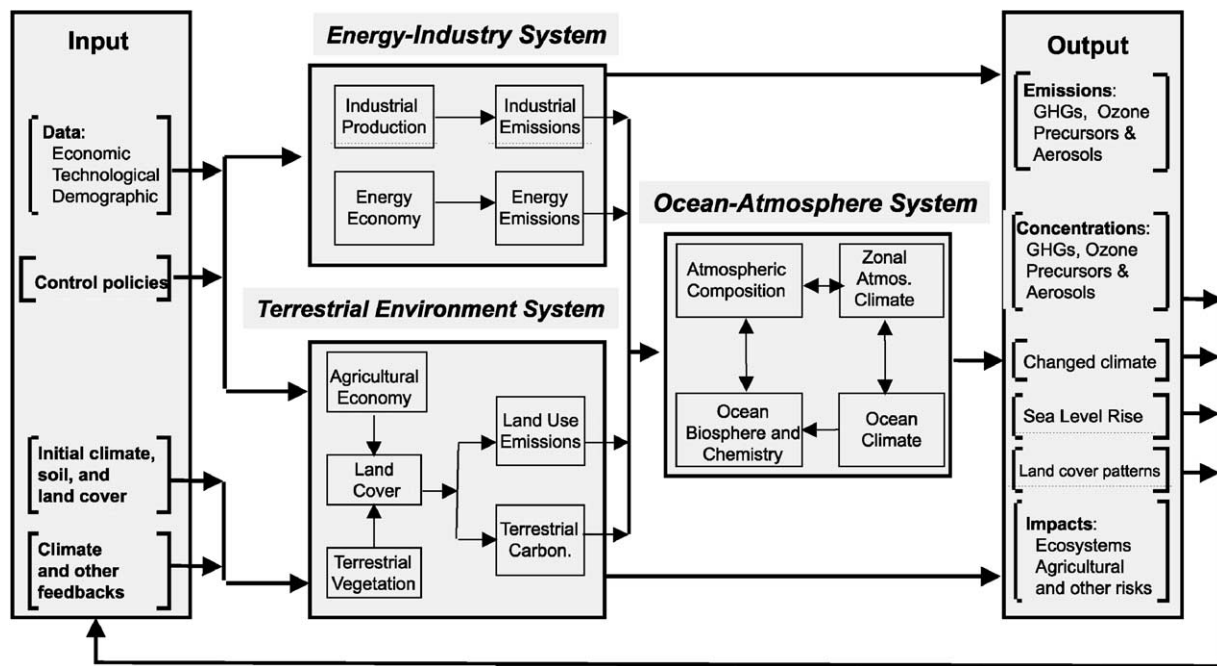


Fig. 2. Flow diagram of the IMAGE 2.1 model.

sectors in 13 world regions (see [Appendix A](#)) based on estimates of industrial production and energy consumption. The *Terrestrial Environment* models simulate changes in global land use and cover on a grid-scale taking into account shifts in the demand and potential productivity of land. These models also compute the subsequent fluxes of gases between the terrestrial environment and atmosphere. The *Atmosphere-Ocean* models calculate the changes in atmospheric composition of greenhouse and other gases, changes in the heat and moisture balance of the earth, and subsequent shifts in temperature and precipitation patterns. Each submodel has been tested either with data from 1970 to 1990, or long-term averages, depending on suitability and availability of data.

In this project, the IMAGE version 2.1.2 is used. In that version the former Energy-Industry models are replaced by the new model TIMER and its emission submodel, which are discussed in the next section.

2.3. The Targets Image Energy Regional (TIMER) model

One of the societal subsystems which is of paramount importance for air pollutant and greenhouse gas emissions is the energy system. This is simulated in the TIMER-model ([de Vries et al., 1999, 2000; van Vuuren and de Vries, 2001](#)), which is a system dynamic simulation model of the world energy system with 17 regions (see [Appendix A](#)). The 17 regions of TIMER correspond to the regions of the (up-coming) version 2.2 of IMAGE that was not available for this project. Accordingly the TIMER output on biofuel demand and emissions from energy use and industrial processes were

converted to the 13 regions of IMAGE 2.1 (see [Appendix A](#) for further details).

A combination of bottom-up engineering information and specific rules and mechanisms about investment behavior, fuel substitution and technology is used to simulate long-term structural dynamics of the energy system. The output is a rather detailed picture of how energy demand, fuel costs and competing supply technologies develop over time in the different regions. The TIMER model and its model calibration for the 1971–1995 period are described in [Rogner \(1997\)](#).

2.3.1. Modeling energy use

The energy demand (ED) submodel of TIMER determines demand for fuels and electricity in five sectors (industry, transport, residential sector, services and other) based on structural changes in the economy, autonomous and price-induced changes in energy-intensity ('energy conservation') and price-based fuel substitution. Next, the demand for electricity is fulfilled by fossil-fuel-based thermal power, hydropower and a non-thermal alternative (solar, wind, nuclear). The latter penetrates the market based on relative costs and learning. This is simulated in the electric power generation (EPG) submodel. The exploration and exploitation of fossil fuels (either for electricity or direct fuel use) is simulated in the Fossil Fuel (FF) submodel, using concepts and data on depletion and innovation dynamics. Biofuels can penetrate the market for liquid and gaseous fuels, once they become competitive with fossil fuels by a combination of fossil fuel resource depletion on the one hand and biofuel learning-by-doing on the other.

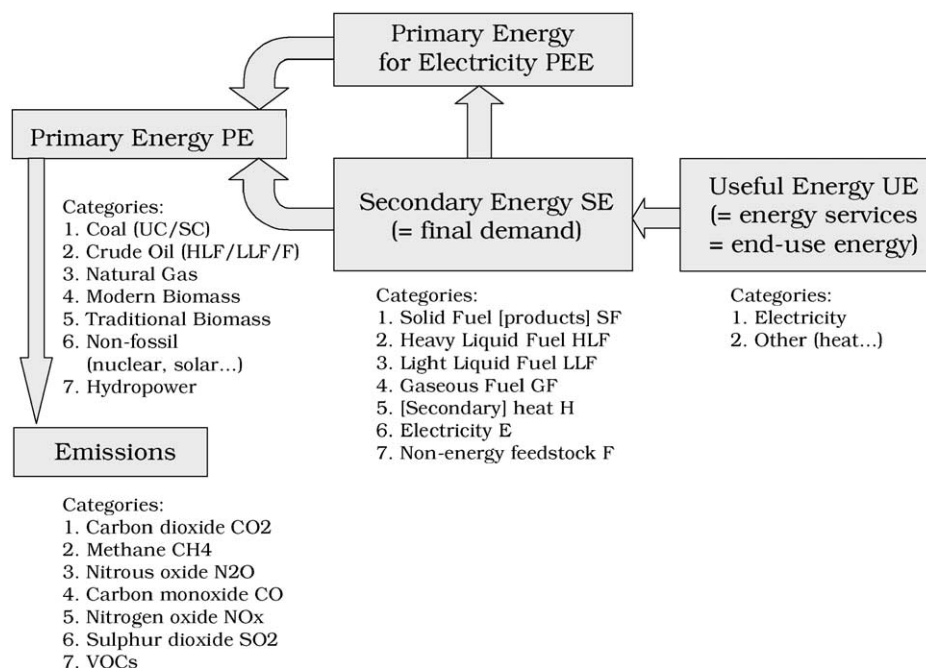


Fig. 3. Flow scheme for the emission calculation in the TIMER/IMAGE model.

Allocation of market shares among competing fuels and of investments among competing options are based in the TIMER model on a multinomial logit formulation. For calibration and scenario analyses, this formulation is extended with shadow prices and exogenous market constraints to simulate real-world phenomena such as perceived advantages or costs of certain fuels or technologies in certain markets not incorporated in the price. Another important aspect is the endogenous formulation of technological development. It is described in terms of log-linear learning curves with exogenous, time-dependent learning coefficients (or progress-ratio's) which indicate the reduction in a cost or performance parameter per doubling of cumulated production ('learning-by-doing') (IEA, 2000). Such learning curves are used in the model for price-induced energy efficiency improvements, fossil fuel production, non-fossil based electricity¹ and biofuels.

The TIMER model is soft-linked to exogenous demographic and macro-economic models and results. We do not account for any feedback from the energy system to these drivers, neither in the baseline nor in the mitigation scenarios; we realize that this is an important limitation. Fig. 3 shows the categories and the flowsheet indicating how the demand for useful energy as derived from population and economic activity projections is converted into greenhouse gas emissions.

¹ For non-fossil based electricity two learning curves are used, one representing nuclear power and one representing solar, wind and other renewables (not hydropower). As already more cumulative output is generated by nuclear power, learning in 'standard' scenarios will be slower for nuclear power than for the second group.

2.3.2. The Energy-Industry Emission submodel

In the Energy-Industry Emission (EIE) submodel, carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), and sulfur dioxide (SO₂) emissions from the energy system and industrial production are calculated. This is done by applying emission factors to the secondary fuels combusted in the regions. In addition, emissions of CH₄ and VOC from the production and transport of coal, oil and gas are taken into account. The methodology is an updated version of the one described in (de Vries et al., 1994). The number of regions is extended from 13 to 17 and a few other changes have been made:

- Emission factors for the different energy sectors and energy carriers for the period 1970–1995 are based on aggregated data from EDGAR 2.0 (Olivier et al., 2001).
- CH₄ emissions from coal mining are calculated taking into account the different emission factors and shares of surface and deep coal mining.
- Emission factors were estimated for 1995–2100 in accordance with the SRES storylines, as described in de Vries et al. (2000).
- A more refined calculation of the SO₂ emissions from fossil fuel combustion by combining data on regional fuel consumption and on fuel properties.

For each region sulfur emissions $E_{\text{SO}_2, \text{UNM}}$ are calculated assuming there are no end-of-pipe techniques such as flue gas desulfurization (FGD) applied:

$$E_{\text{SO}_2, \text{UNM}} = \sum_{\text{S, EC}} \text{RSE}_{\text{S, EC}} f_{\text{Sul, S, EC}} (1 - f_{\text{ash, S, EC}}) \quad (1)$$

where RSE is secondary energy demand, f_{Sul} the sulfur content of energy carrier, f_{ash} the fraction of sulfur retained in ash, S the sector (industry, transport, residential sector, services and other), EC the energy carrier (coal, heavy fuel oil, light fuel oil, gas, modern biofuel, traditional biofuel).

In the following we will refer to $E_{\text{SO}_2, \text{UNM}}$ as *unmitigated SO₂ emissions*. In Section 3.4, it is described how the mitigated SO₂ emissions (i.e. including end-of-pipe technologies) are derived.

Emissions from industrial processes are calculated by multiplying the level of industrial activity with emission factors. Future levels of industrial activity are computed by scaling the 1990 activity level based on the development of energy use in industry as calculated by TIMER. The industrial processes taken into account are: cement production (CO₂, NO_x), feedstock use of energy carriers (CO₂), chemical manufacturing (NMVOC), adipic acid production (N₂O), nitric acid production (N₂O, NO_x), ammonia production (NO_x), solvent use (NMVOC), steel and iron industry (CO, NMVOC), sulfuric acid production (SO₂), copper melting (SO₂), and miscellaneous (NMVOC, SO₂). The methodology as described in (de Vries et al., 1994) has been updated with the most recent emissions factors of EDGAR 2.0, and the inclusion of chemical feedstocks.

Halocarbon emissions are set exogenously, based on the IPCC SRES emissions scenarios developed by Fenhann (2000). The emissions of the halocarbons regulated in the Montreal Protocol, i.e. the CFCs, HCFCs, halons, carbon tetra chloride and methyl chloroform follow, similar as in the IPCC SRES emissions scenarios, the Montreal protocol scenario (A3) of WMO/UNEP (1999). The emissions of the three groups of greenhouse gases, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF₆) (all new gases compared to the IMAGE 2.1 model), which in the Kyoto Protocol were added to the gases CO₂, CH₄ and N₂O in the UNFCCC, are also based on Fenhann (2000).

2.3.3. Uncertainty analysis of the TIMER model

For an earlier version of the IMAGE Energy-Industry System (de Vries et al., 1994) UNCSAM uncertainty analysis indicated that in the short term the calculated emissions are most sensitive to the assumptions on the specific costs of energy efficiency and the accepted payback times of consumers. In the longer term, however, the assumptions on growth elasticity and autonomous efficiency improvements become the more important determinants. A formal uncertainty analysis for the first one-region version of TIMER (TIME) indicated that the various feedback loops tend to have a stabilizing effect, offsetting various uncertainties (de Vries et al., 1999). For instance, a higher learning coefficient in biofuel production causes faster substitution of oil and gas; this will slow down the oil and gas resource base and hence the oil and gas prices decrease—which in turn slows down biofuel competitiveness.

In the present simulations, a large uncertainty in outcome stems from the uncertainty in the driving forces: population growth and economic growth and structure. Indeed, the use of two different GDP-growth trajectories is one of the ways to deal with uncertainty (cf. Nakicenovic et al., 2000).

The uncertainties in the translation of driving forces into energy and emission fluxes are strongly related to the assumptions listed in Appendix C. Preliminary analyses, as part of a more comprehensive uncertainty analysis (Sluijs, 2000), indicate that calculated energy demand is most sensitive to the so-called autonomous energy-efficiency investments (AEEI) and whether a purchasing-power-parity-correction on economic growth is applied. On the supply side, the assumption on the rate of technological progress are a dominant uncertainty factor with regard to primary energy use and related emissions.

2.4. Model to calculate European ammonia emissions

Long-term ammonia (NH₃) emission scenarios (i.e. up to 2100) have not been derived in the past. The RAINS model calculates European NH₃ emissions per country up to the year 2010 based on specified agricultural pathways. IMAGE calculates greenhouse gas emissions per region up to 2100, but not NH₃ emissions. Thus, there was a need in this project to derive an approach to calculate European NH₃ emissions up to 2100.

In Europe, the following sources of ammonia (NH₃) emissions are important (Klaassen, 1991; Klaassen, 1992):

- Livestock farming: dairy cows, other cattle (including buffaloes), pigs, poultry, sheep and goats, and horses.
- Nitrogen fertilizer use.
- Industry (fertilizer and ammonia production plants).
- Other anthropogenic sources (i.e. other industry, waste treatment, human respiration).

Ammonia emissions are assumed to be proportional to the level of activity of these emission sources. Therefore, it is important to estimate these future activity levels in Europe. Most of these activities are modeled per region in IMAGE up to 2100:

- The Agricultural Economy Model (AEM) of IMAGE 2.1 computes the livestock population driven by the demand for animal commodities, which is in turn driven by population and income growth (Zuidema et al., 1994). AEM distinguishes seven livestock groups: (1) dairy cows, (2) other cattle, (3) pigs, (4) sheep and goats, (5) poultry, (6) horses, and (7) mules. Thereby, the latter two animal types are exogenously set and not modeled.
- In addition, AEM calculates the amount of fertilizer use.
- The EIE submodel (see Section 2.3.2) calculates the industrial ammonia production by scaling the 1990 activity level based on the development of energy use in industry.

In summary, for all the relevant emission sources of NH₃ activity levels are modeled in IMAGE. NH₃ emission factors

for the IMAGE regions OECD Europe, Eastern Europe and the former USSR are specified based on the emission factors in RAINS (Klaassen, 1992). Regional emissions are calculated by multiplying the activity levels calculated by IMAGE with the emission factors.

A multitude of studies on mitigation measures for NH_3 have been presented in the past (e.g. Sutton et al., 1998). The scenario analysis done with RAINS for the Gothenburg Protocol is one of the first that calculated resulting reduction levels per European country (Amann et al., 1999). These results should be integrated in a second phase. In this project, no mitigation measures were assumed (according to the Gothenburg Protocol NH_3 emissions should be reduced by 25% in 2010 relative to 1990) (UN-ECE, 1999).

2.5. Calculating regional air pollution: source-receptor matrices

2.5.1. Standard approach

Source-receptor matrices (SRMs) are used to calculate grid-scale atmospheric concentration and deposition of air pollutants from country-scale emissions. These matrices summarize the various chemical and transport processes of sulfur, nitrogen and other substances in the atmosphere, and link emissions to deposition by linear equations. The present country-to-grid matrices for acidifying pollution are derived from model results of the EMEP Lagrangian Acid Deposition Model (LADM) and are based on actual meteorology for the period 1985–1996 (see Barrett and Berge (1996) for a further description of LADM). The SRMs for annual deposition of sulfur and nitrogen compounds derived in this way have been extensively employed for abatement strategy assessments. They are for example integrated in the RAINS model and have been the basis for the integrated assessment for the Gothenburg Protocol (Amann et al., 1999), (UN-ECE, 1999).

For this project LADM has been rerun for 1985 to 1996 to derive monthly and annual SRMs for concentrations of SO_2 , NO_2 , and NH_3 that were not routinely available. Within the AIR-CLIM project the air pollution concentrations and deposition in Europe have been calculated with these SRMs (called *present SRMs* in the following).

2.5.2. Sensitivity of air pollution to climate change

It is likely that climate change will lead to long-term and seasonal changes in weather patterns. These changes may, in turn, alter the dispersion, chemical conversion and removal of pollutants in the atmosphere. Thus, one task within AIR-CLIM was to model air pollution in Europe under climate change. For this purpose climate-dependent SRMs were derived by running LADM with meteorological data from a climate model.

In LADM the transport term of the (two-dimensional) mass balance equation is described according to trajectories. These trajectories are calculated from horizontal wind vectors. Physically, pollutants are removed from the

Table 1

Meteorological data relevant in LADM (Barrett and Berge, 1996)

Meteorological data	Factor affected
Horizontal wind speed at pressure level 925 hPa	Trajectories
Ground precipitation	Wet deposition
Vertical velocity at pressure level 850 hPa	Exchange with layer above mixing layer
Surface pressure	Dry deposition
2 m temperature	Dry deposition
Turbulent stress	Dry deposition
Turbulent heat flux in the surface layer	Dry deposition
Relative humidity at pressure level 925 hPa	Dry deposition
Mixing layer height (derived from temperature gradient)	Emission source intensity
Deposition	
Cloud cover	NO_2 dissociation
Temperature at 925 hPa	Chemical reactions

atmosphere by dry and wet deposition. Wet deposition is caused by precipitation, and dry deposition is influenced by turbulence, surface pressure, temperature, and relative humidity. Chemically, pollutant species are removed by chemical conversion processes. These are influenced by temperature, cloud cover, and the height of the mixing layer. Table 1 summarizes the meteorological data that influence the calculations of LADM.

Due to limited computer power for long climate simulations only low resolutions can be used in global coupled atmosphere-ocean general circulation models (CGCMs) (at present 2.8° or 5.2° grids equivalent to grid lengths of about 300 or 500 km at the equator). With such resolutions the development of weather systems cannot be modeled appropriately because land-sea and orographic effects are not captured (Cubasch et al., 1999). In the time-slice technique a CGCM simulation is repeated for a certain period (e.g. 10 years) using a higher resolution atmospheric model (AGCM) which takes initial and sea surface boundary conditions from the CGCM simulation (Machenhauer et al., 1998). With this technique high resolution simulations can be run relatively fast.

In the SIDDACLICH project Cubasch et al. (1999) carried out (among others) a time-slice experiment with the AGCM ECHAM4. In this experiment, the resolution was 1.1° (about 100 km grid length at equator). The boundary data were taken from a ECHAM4/OPYC[PM1] run with a resolution of 2.8° for the IS95a scenario (an update of IS92a) without sulfur. Six-hourly data were calculated for two timeslices: 1971–1980 (control period) and 2041–2050 (future period). In the future period the CO_2 concentration is doubled relative to pre-industrial levels and the global temperature rises by about 2 K compared with the control period.

LADM was run for these two decades (1971–1980 and 2041–2050) using the 1996 EMEP S and N emissions for all years. Therefore, all differences between the results for the two timeslices are only due to changes in the meteorological data. The calculated deposition of sulfur and nitrogen is in

most countries up to 12% lower in the future period than in the control period. Notable exceptions are the deposition of sulfur in some parts of Eastern Europe which increases up to 5% and the deposition of oxidized nitrogen in other parts of Eastern Europe which increases up to 2%. The retention of the emitted reduced nitrogen within the EMEP area is about 13% lower in the future period, and the retention of emitted sulfur and oxidized nitrogen about 2%, i.e. exports from Europe are somewhat increased. With few exceptions the net budget (import minus export) of deposition per emitting country decreases slightly. The inter-annual variability is not or only marginally affected. This experiment and its results are described in further detail by Mayerhofer (2001).

To apply the SRMs for the two timeslices in the AIR-CLIM project they have to be interpolated for different scenarios and years. For this interpolation parameters have to be used that are available from IMAGE 2.1.2, restricting the choice to temperature and precipitation. As precipitation is calculated in a different way in IMAGE than in ECHAM4, the average temperature in the EMEP area is used to linearly interpolate the SRMs between the future and the control period to calculate the SRM for a specific scenario and year (see Appendix B for the calculation formula).

2.5.3. Uncertainties

Various parts of the method contribute to the uncertainties of the air pollution levels calculated for a given set of emissions: (1) how well LADM calculates the levels for given S and N emissions, (2) what errors are added by using SRMs instead of LADM for another set of emissions (*linearity question*), (3) what errors are incurred by applying the present SRMs for a changed climate or by applying the interpolated climate-changed SRMs.

Analyses have shown that LADM reliably reproduces the pattern of transboundary acidifying pollution in Europe (Tarrasón et al., 1998). In general, it is accepted that over long time and space scales the assumption of linearity between SO₂ emissions and deposition is appropriate (see Alcamo et al., 1987). The composite uncertainty of total deposition ranged from 10 to 20% in an uncertainty analysis of modeling long-range transport of sulfur in the present climate with the present SRMs (Alcamo and Bartnicki, 1990). This was less than the sum of individual uncertainties and indicated a compensation of errors. Thus, the use of a linear source-receptor matrix instead of the full model can be justified. The error for nitrogen could be larger, however, it has never been investigated in detail.

When the present SRMs are used to calculate air pollution levels under climate change, an additional error is incurred as changed weather pattern are not taken into account. The sensitivity analysis with the available climate-changed SRMs shows that this error seems not significant averaged over large regions. But, while the various GCMs agree rather well with respect to the global average temperature, they differ significantly for precipitation and for regional climate (Houghton et al., 1995). Thus, it would be of special

interest to see what the results based on meteorology from another GCM would be. Another issue is what error is made by interpolating the SRMs for the future and the control period for other scenarios and years. In that case the compensation of errors when applying linearized equations might for example no longer be valid.

3. Scenarios

3.1. Overview

One of the objectives of the AIR-CLIM project is to identify and evaluate strategies for controlling both regional air pollution and climate change in Europe. To achieve this objective scenarios with different combinations of greenhouse gas policy and air pollution policy have to be analyzed. As start scenarios to which these policies are applied two of the so-called SRES scenarios of the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) are used (see Section 3.2). These are modified by greenhouse gas policies (no policy, stabilization at about 550 or 450 ppmv by the year 2100, respectively) (see Section 3.3), and air pollution policies (present policies and advanced policies) (see Section 3.4). The result are eight scenarios (Table 2) that allow us to assess the effect of the policies by themselves or in combination. Fig. 4. visualizes how the combinations of policies add up in the two scenario worlds.

3.2. The baseline scenarios: storylines and driving forces

The scenarios presented here consist of narratives called ‘storylines’ plus numerical estimates of the trends of different variables computed simulation models. In 1996 the Intergovernmental Panel on Climate Change (IPCC) asked a group of experts to construct a new set of global greenhouse gas emissions scenarios in preparation for the Third Assessment Report. The scenarios should, amongst other requirements, be without any additional explicit climate policy (i.e. the Kyoto Protocol is *not* taken into account)

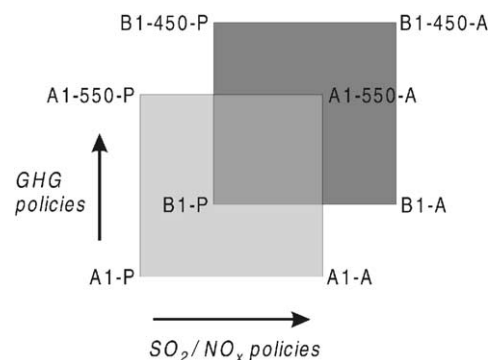


Fig. 4. AIR-CLIM scenarios: combinations of start scenarios, greenhouse gas (GHG) policies and air pollution policies (for SO₂ and NO_x).

Table 2
Overview of AIR-CLIM scenarios

	Start scenario	Greenhouse gas policies	SO ₂ /NO _x policies
A1-P	A1	None	Present policies
A1-A	A1	None	Advanced policies
A1-550-P	A1	To achieve 550 ppm stabilization	Present policies
A1-550-A	A1	To achieve 550 ppm stabilization	Advanced policies
B1-P	B1	None	Present policies
B1-A	B1	None	Advanced policies
B1-450-P	B1	To achieve 450 ppm stabilization	Present policies
B1-450-A	B1	To achieve 450 ppm stabilization	Advanced policies

P: present air pollution policies (i.e. compliance with Gothenburg Protocol and equivalent measures in regions without policies up to now), A: advanced air pollution policies (i.e. assume reductions increase after compliance with Gothenburg Protocol).

Table 3
Characterization of the four SRES scenarios (the scenarios in *italics* are used in AIR-CLIM)

	'Open' world with high convergence (globalization)	'Closed' world with low convergence (pluralism)
Strong and explicit materialist, free-market orientation	<i>A1</i>	<i>A2</i>
Strong and explicit sustainability and equity orientation	<i>B1</i>	<i>B2</i>

and cover all greenhouse gases. Four sets of qualitative storylines describing possible world futures were developed, differentiated according to the degree of globalization and to value orientation (see Table 3) (Nakicenovic et al., 2000).²

Two out of the SRES baseline emissions scenarios for the world at large have been worked out in more detail in the AIR-CLIM project, with a focus on the regions OECD Europe, Eastern Europe and the former USSR (see Appendix A for region classification). It should be recalled, however, that all results refer to model simulations for the world at large. A1³ and B1 are selected because they cover most of the emission range as identified by the SRES scenarios—especially for the next 50 years.

The A1 future is largely determined by the market dynamics of new consumer goods and services. The average income between regions is converging and within regions wealth slowly trickles down to the population at large. Global governance is confined to guiding the debates about the 'level playing field' in institutions such as the World Trade Organization. Environmental issues are dealt with only as far as the more affluent citizens express their concern about urban air and water quality, loss of natural habitats etc. (Riahi and Roehrl, 2000). In the B1 future there is a more balanced interplay between entrepreneurs and governments, with forms of cooperation and regulation. Consumers and

producers are oriented towards sustainable development, resulting among others in an accelerated transition towards a service- and information-economy. Resource efficiency and avoidance of extreme income disparities are explicit policy objectives, formulated and implemented at all governance levels (de Vries et al., 2000).

The major driving forces in the two scenarios are population growth and economic growth as expressed in Industrial and Service Value Added and Gross Domestic Product. The population and economic scenarios used here have been implemented by the Phoenix model (Hilderink, 2000) and the WorldScan model (CPB, 1999). In both scenarios, world economic growth continues at an average 2.7% per year (A1) and 2.2% per year (B1), respectively, and population stabilizes around 2050 at about nine billion people and declines afterwards—consistent with the widely held assumption that the demographic transition is accelerated with rising income.⁴ Fig. 5 shows the population paths for the three regions focussed upon in this paper, and a comparison with a recent other scenario for OECD Europe (European Commission, 1999). Population is projected to peak in both scenarios and in all three regions by mid-century. The projection for OECD Europe is slightly above the EU projection, mainly because of different assumptions about migration related to the 'globalizing' nature of both the A1 and B1 scenario.

Economic activities grow in OECD Europe at roughly the same rate as in the last 50 years in the A1 future and, after 2030, somewhat less in the B1 world (Fig. 6). The share of the service sector increases in scenario B1 somewhat faster

² For more details on the SRES IPCC scenarios, see www.grida.no/climate/ipcc/index.htm, www.ipcc.org, www.ciesin.org and Nakicenovic et al. (2000) and Kram et al. (2000).

³ In SRES, within the A1 family three subgroups are distinguished depending on the role and direction of coal use and technological change: A1B[alanced], A1F[ossil] and A1T[echnological]. Here, A1B is used throughout and is called A1.

⁴ In reality, this relationship is rather complex, see e.g. Hilderink (2000), MacKellar et al. (1998).

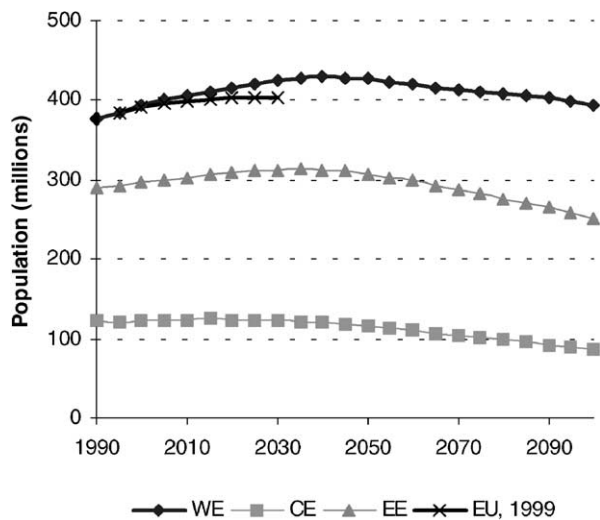


Fig. 5. Population trajectories in A1 and B1 scenario, and in EU-scenario (until 2030).

than in scenario A1 (Fig. 7), in line with the narratives. In the 1990–2030 period, growth rates compare well with those used recently by the DG Energy (European Commission, 1999). In Eastern Europe and the former USSR, economic growth is higher because both regions are assumed to catch up in the globalizing A1 and B1 worlds. In the market world A1, the projected economic growth is higher than in the B1 world and by 2100 income in A1 is almost twice that in B1 (Table 4).

In scenario construction, assumptions have to be introduced for a large set of parameters in accordance with the storyline. Regarding the energy system, the assumptions for the B1 scenario have been described elsewhere in detail (de Vries et al., 2000) and the main assumptions for the present scenario exercise are summarized in Appendix C. In both scenarios but more markedly in the B1 than in the A1 world,

the energy system is characterized by continuing dematerialization and technology improvements and by a preference for more environmentally friendly fuels. The latter shows up in the form of slowly increasing taxes on coal to reflect the internalization of external costs. The underlying choices for energy efficiency and environmentally friendly fuels are motivated by environmental problems other than climate change but do contribute to carbon emission reduction—the so-called co- or ancillary benefits (IPCC, 2001).

3.3. The greenhouse gas policies: stabilizing greenhouse gas concentrations

The combination of an orientation towards sustainable development and lower and less energy-intensive levels of economic activities leads to significantly lower CO₂ emissions in the B1 than in the A1 scenario (see Section 5). This orientation on sustainable development presumes that, with rising income, people are willing to invest more in clean urban air and better public transport and that their lifestyles develop towards more service-oriented less material-intensive needs (cf. Appendix C). It implies that additional income is increasingly spent on high-quality food, on health and child care, and on communication and entertainment, to mention a few.

As a consequence scenario B1 leads to an equivalent CO₂ concentration of less than 600 ppmv by the end of the century (de Vries et al., 2000); in the A1 scenario it exceeds 750 ppmv. Nevertheless, given the mounting evidence that significant climate change with adverse impacts is to be expected from levels >450 ppmv by the year 2100 (IPCC, 2001), there is a need for emission reduction in both scenarios. As part of the AIR-CLIM project, we have developed two mitigation scenarios: A1-550 with the CO₂ concentration stabilized by 2100 at about 550 ppmv and B1-450

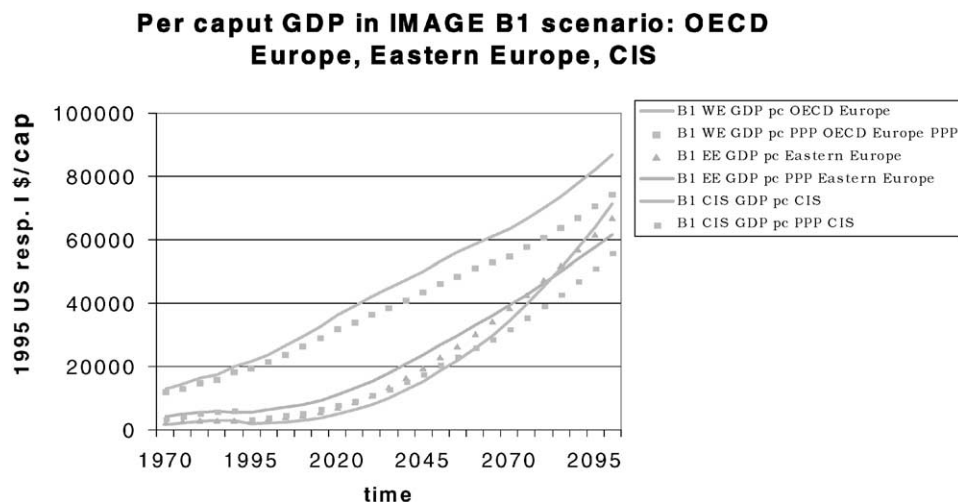


Fig. 6. Economic growth (GDP per cap) in the B1 scenario.

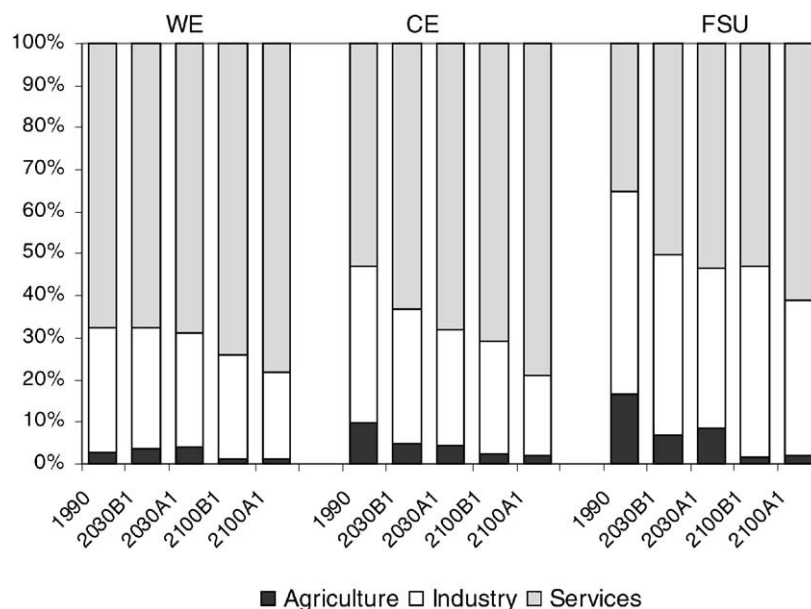


Fig. 7. Composition of GDP in the A1 and B1 scenario.

Table 4

Economic growth: annual change in GDP per cap

	1990–2010 (%)	2010–2020 (%)	2020–2030 (%)	2030–2050 (%)	2050–2100 (%)
OECD Europe					
A1	1.8	2.0	1.9	1.6	1.6
B1	1.9	2.1	1.5	1.2	1.0
EU, 1999	1.9	1.8	1.6		
Eastern Europe					
A1	4.0	5.7	6.1	4.1	2.1
B1	2.1	4.5	4.7	3.8	2.2
OECD, 1997 ^a	2.8	3.5			
Former USSR					
A1	1.7	6.4	6.3	4.6	2.6
B1	−0.1	5.4	5.0	4.3	2.7
OECD, 1997 ^a	0.0	5.4			

^a OECD (1997) as interpreted and discussed in van Vuuren and Bakkes (1999).

at about 450 ppmv.⁵ The options and costs of greenhouse gas emission reductions depend first of all on the baseline scenario. Other aspects are the timing of measures, the responses in the form of technological change, the potential for emission trading and joint implementation and the possibility of recycling tax revenues (van Vuuren and de Vries, 2001).

In an A1-future, there will be enough capital, technological skills and openness to introduce mitigation measures and policies worldwide in an attempt to keep CO₂ concentrations <550 ppmv. The dominant market-orientation will favor

policy instruments such as emission trading and strongly prefer support of technological innovations over regulations or life-style changes. In our implementation, we assume that high-tech innovations towards energy-efficiency and renewable energy supply are the prevailing response to emission reduction pressures.⁶ In a B1 world, aiming for 450 ppmv CO₂ concentration stabilization, governments are assumed to formulate preventive and adaptive action. Industrialized countries take the lead and support the less developed regions by transfer of energy-efficiency and renewable energy related technologies. Internalization of associated costs, by means of energy taxes or other financial instruments, is a

⁵ Thereby the global CO₂ concentration was calculated with the meta-IMAGE 2.1 model that is directly integrated in TIMER (den Elzen, 1998). This model uses 'standard' land-use emissions that do not necessarily agree with those calculated by IMAGE for this scenario.

⁶ Other implementations are, of course, possible, both for an A1-world and a B1-world. For instance, a focus on clean-coal technologies in combination with carbon removal and storage.

favorite policy instrument. Finally, if adverse climate change consequences are expected or occurring, in a B1 world there will be consideration of both winners and losers in formulating and implementing abatement and adaptation measures—for instance, in the form of a global compensation fund.

The main instrument used to construct our mitigation scenarios is the introduction of a world-wide uniform carbon tax, as a proxy of all climate policies focusing on the world energy system (see e.g. (Criqui et al., 1999; van Vuuren and de Vries, 2001)). It is levied at the consumer end of the chain. Application of such a tax implies that the marginal costs in different regions are more or less equalized. Such a scenario requires some form of international cooperation, for instance emissions trading. The model simulates several different responses which lead to lower CO₂ emissions:

1. Price-induced investments in energy-efficiency, which in turn bring down the energy-efficiency supply cost curve as a result of learning-by-doing (economies of scale and innovation).
2. Price-induced fossil fuel substitution with associated effects on the rate of depletion and innovation in fossil fuel supply and demand.
3. Changes in the trade patterns of (fossil) fuels as a consequence of changing regional (fossil) fuel prices.
4. Price-induced acceleration of investments in non-fossil options such as wind/solar energy, nuclear energy and biofuels, bringing down their specific investment costs in the process of learning-by-doing.

Thus, TIMER simulates a variety of technological and economic changes in the energy system in response to carbon taxes. A single carbon tax profile is introduced for all regions which linearly increases to US\$ 750/tC by 2080 and is thereafter constant in the A1-550 scenario and to US\$ 200/tC by 2080 and is thereafter constant in the B1-450 scenario. These tax profiles are the outcome of an adjustment procedure such that the resulting world carbon emissions from fossil fuel combustion led to stabilization around 2100 at the targeted CO₂ concentration level (den Elzen et al., 2001). We use the change in user costs, that is, the product of final energy carriers and their associated prices for consumers, as an indicator of the system-wide emission mitigation costs (see van Harmelen et al., 2001). As the model simulates explicitly capital stocks and technical improvements, it captures at least some aspects of the inertia and technological change issue in the discussion on costs and optimal timing of mitigation strategies (Grubb, 1997; Ha-Duong et al., 1997; van Vuuren and de Vries, 2001).

3.4. The air pollution policies

For the SRES scenarios it was assumed that sulfur emissions will also be controlled increasingly outside of the OECD as incomes rise and convergence in environmental policies continues. It was assumed that this will happen in

the absence of explicit climate policy measures (Nakicenovic et al., 2000).

As it is the objective of this study to identify joint targets and strategies to control regional air pollution and climate change, it is necessary as a first step to derive baseline scenarios that include neither climate policies *nor* air pollution policies beyond those already in place or agreed upon (*present air pollution policies*). These baseline scenarios are compared to scenarios with *advanced air pollution policies*. It has to be noted that neither of these two air pollution policies concur with the sulfur control pathways of the original SRES scenarios.⁷

SO₂ and NO_x emissions are determined by (1) the energy demand and energy carrier mix as well as the level of industrial production, and by (2) the degree of end-of-pipe measures. In the following so-called unmitigated and mitigated emissions are distinguished. *Unmitigated emissions* are those emissions when no end-of-pipe techniques are applied (see Section 2.3.2). *Mitigated emissions* are the remaining emissions when end-of-pipe techniques are taken into account. The *end-of-pipe reduction rate* is the difference between unmitigated and mitigated emissions relative to the unmitigated emissions.

The unmitigated SO₂ and NO_x emission pathways result only from the change in the driving forces over time (via the modeled energy use and industrial production). By comparison, the mitigated emission pathways computed not only from driving forces but also from a set of rules that specify the end-of-pipe rate of emission reduction. These rules assume that emissions will be reduced because of environmental concerns but do not take into account the costs involved. This is parallel to the approach taken to derive mitigation scenarios of CO₂ emissions in this project which are also principally driven by environmental concerns.

3.4.1. Present air pollution policies in Europe

For Europe the most recent international agreement on mitigation of SO₂ and NO_x is the so-called Gothenburg Protocol (Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution to Abate Acidification, Eutrophication and Ground-Level Ozone) (UN-ECE, 1999). In the scenarios with the present air pollution policies the emissions reach the Gothenburg levels in 2010 and do not exceed these thereafter. After 2010 emissions either stay on this level, or drop below it because of reduced energy use or a change in the fuel mix.

3.4.2. Advanced air pollution policies in Europe

For these scenarios it is assumed that the end-of-pipe reduction rate grows after 2010 following a logistic function up to a maximum value (95% for SO₂ and 85% for NO_x, these maximum values are based on a literature review

⁷ In the EIE submodel of TIMER there are also implemented a set of sulfur controls pathways consistent to the original SRES scenarios (de Vries et al., 2001). These control pathways, however, are not used here.

of the technically feasible). The parameters of the logistic function are determined by assuming that reductions are zero in 1980 and are sufficient to comply with the Gothenburg level in 2010.

As NO_x has only a minor effect on climate (via its influence on ozone) the unmitigated emissions have been used outside of Europe. For SO_2 for North America and Japan the same rules as for Europe have been applied using emission caps from mitigation agreements equivalent to the Gothenburg Protocol.

3.4.3. Present air pollution policies outside OECD

For non-OECD regions a somewhat different approach is used to derive the SO_2 emissions. First, the so-called *Pollutant Burden Approach* (PBA) is used to determine the point in time at which emission reductions begin (Onigkeit and Alcamo, 2000).⁸ It is assumed that regions outside of Europe, North America and Japan start reducing sulfur dioxide emissions when the respective environmental impacts reach about the same magnitude as the environmental impacts in Europe, North America, and Japan at the time when they began to reduce their emissions.⁹

Second, once emission reductions begin, the same type of logistic function discussed above for Europe is used to set the end-of-pipe rate of emission reduction.

When the regional emissions have decreased to 50% of the peak emissions, the end-of-pipe reduction rates remain constant. This assumption has been made to be equivalent to the policy-regions, for which no further actions are assumed after 2010 in this policy case. The emission levels in the policy regions in 2010 are roughly about half of those in 1980 which is assumed to be the reduction start year of the policy regions.

3.4.4. Advanced air pollution policies outside OECD

The same approach is applied as for the present air pollution policies outside OECD, with one exception: the end-of-pipe reduction rates continue to grow until the maximum levels are reached (95% for SO_2 , 85% for NO_x).

4. Energy use

Model results for the two baseline scenarios (A1 and B1)¹⁰ and the two mitigation scenarios (A1-550 and B1-450)

⁸ The original PBA is a stochastic method but here we use only average values of all parameters.

⁹ As a measure for the environmental impacts a *pollutant burden* is calculated. It is defined as a critical percentage of the land area of a region in which a critical level of emission flux (i.e. the annual rate of SO_2 emissions per unit area) is exceeded (see Onigkeit and Alcamo (2000) for a description of how the critical level of emission flux was derived).

¹⁰ The air pollution policies implemented here do not affect energy use and industrial processes. That means that the energy use and the greenhouse gas emissions of e.g. A1-P and A1-A are identical. Accordingly, in the following A1 refers to A1-P and A1-A and A1-550 to A1-550-P and A1-550-A, etc.

are shown in Appendix D. Between 1971 and 1995, the ratio between energy and GDP (energy intensity) has decreased strongly in most countries. Reasons for this include the improvement of energy efficiency (the ratio between energy services provided and energy use) and shifts within the economy, such as a shift towards a service economy (see e.g. Schippers and Meyers (1992)). However, at the same time energy consumption itself has increased. For our model simulations, secondary energy use is an important variable as it is the basis for most of the emission calculations and costs of mitigation measures (see Section 2.3.2 and van Harmelen et al. (2001)).

In the A1 scenario, per capita secondary energy use keeps increasing despite declining energy-intensity with a saturation tendency by the end of the 21st century at levels of 230 GJ per cap per year or 2–3 times the 1995-level. In the B1 scenario, the assumption of a less energy- and material-intensive nature of economic activities leads to a stabilization and then decline in per capita secondary energy use within 20–30 years from now at 95 GJ per cap per year. Both the fraction of electricity and of energy for transport keep increasing throughout the scenario period. In the stabilization scenarios, energy consumption decreases significantly, in particular in the A1-550 scenario, where a low priority for energy efficiency in the baseline leaves significant room for improvement. The final level of secondary energy consumption in A1-550 is 180 GJ per cap per year. In the B1-450 this is 85 GJ per cap per year.

Energy inputs for electric power generation reflect the differences in electricity demand between the A1 and B1 scenario: they keep growing in the former towards three times the 1995-level whereas in the latter they peak at less than twice the 1995-level around 2030. However, in both scenarios a significant penetration of initially gas and later non-thermal options (nuclear, solar/wind, etc.) takes place. By 2050, the fraction of fossil fuels in the total generation input is down from 72 to 57% (A1) and 55% (B1) in OECD Europe in A1; in Eastern Europe this fraction declines, too,

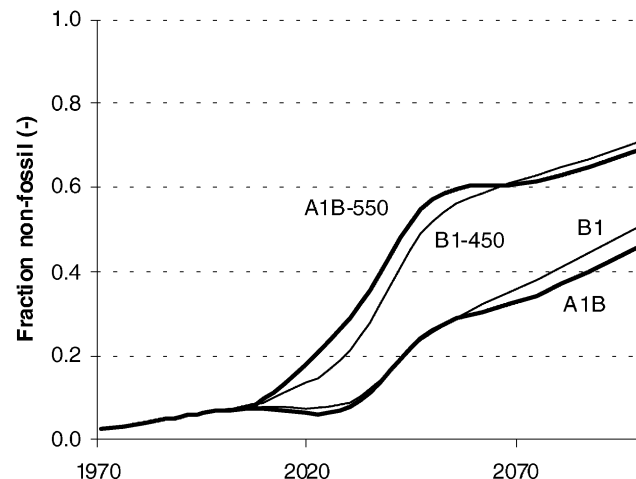


Fig. 8. Role of non-fossil fuels (biomass-derived fuels, nuclear/solar/wind).

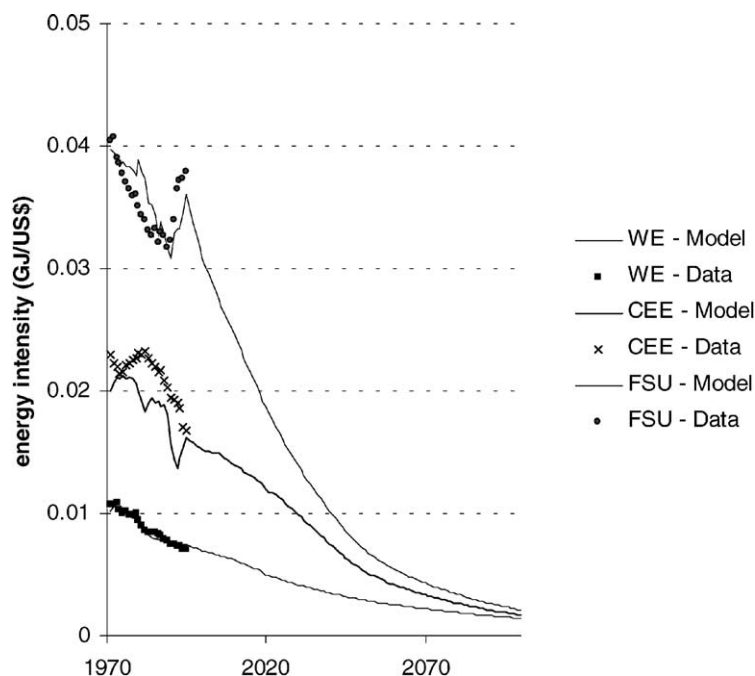


Fig. 9. Primary energy intensity in the B1 scenario vs. historic data.

but less rapidly. In both mitigation scenarios, major changes in the electricity system occur as compared to the baseline. In the A1-550 and the B1-450 scenario the fossil fuel input in 2050 for the three regions combined declines to 16 and 23%, respectively.

Electricity generation costs are the result of three trends: increasing conversion efficiencies of thermal power plants, rising fuel costs and cost decreases in the non-carbon options through learning-by-doing. As a consequence, electricity generation costs tend to rise initially to become more or less constant later on.

Total primary fuel use develops quite differently in the two scenarios. It increases in the A1 scenario with about 80% in 2100 over 1995-values in all three regions, whereas in the B1 scenario it starts declining after an initial rise to 15–20% <1995-values. The fraction of fossil fuels in the total declines across all scenarios and regions to a small bandwidth of 47–54%.

The increasing *role of non-fossil fuels* is clearly seen from Fig. 8. Even in the open A1 and B1 worlds, our simulations suggest a slow but persistent penetration of non-carbon options—biomass-derived fuels and a mix of nuclear, wind and solar power.¹¹ The resulting primary energy-intensity, defined as the ratio between primary energy use and GDP, declines significantly in both the A1 and the B1 scenario, at a rate comparable to the 1971–1995 period in OECD Eu-

rope (Fig. 9). In the two mitigation scenarios, the rate of energy-intensity improvements increase to levels at –2.2% per year which is at the upper end of the historical range.

The fuel and electricity *prices* are the key variable mediating demand and supply. Prices for secondary fuels are calculated from regional and imported fuel costs, add-on taxes and so-called premium factors reflecting externalities such as strategic and environmental aspects not expressed in market prices. Apart from taxes and externalities, coal prices tend to stay rather stable: the supply of cheap coal on world markets acts as a buffer. Oil and gas prices are smoothly rising in both scenarios as the net result of depletion on the one hand, despite the possibility for Europe to import freely from whichever region produces most cheaply, and innovations in fossil fuel production and transport on the other hand. A summary indicator are the so-called user cost, that is, the weighted price of an average unit of energy consumed by the end-users.¹² Our analyses indicate that user cost rise in all scenarios and regions but (1) somewhat faster in the A1 than in the B1 future, at least in the longer term, (2) much more in Eastern Europe and former USSR than in OECD Europe, (3) the costs of climate change policies may be significant in absolute terms but they are rather small (<30%) in relative terms, and (4) some sectors in some regions e.g. industry and transport in the former USSR will be hit hardest by the assumed rise in carbon value (see also van Harmelen et al., 2001). These results reflect, amongst others, the presumed removal of subsidies on coal, the forced reduction in

¹¹ We explore also the options of nuclear and non-nuclear (solar, wind, etc.) separately. In the A1 scenario, the share of renewable energy, that is, of non-fossil excluding nuclear, in the total non-fossil is about half; in the B1 future over three-quarter.

¹² Note that, in this definition, the trend towards a larger share of electricity, a high-quality energy form, will cause a rise in user cost.

Investment flows A1B and B1 scenario Western, Central and Eastern Europe

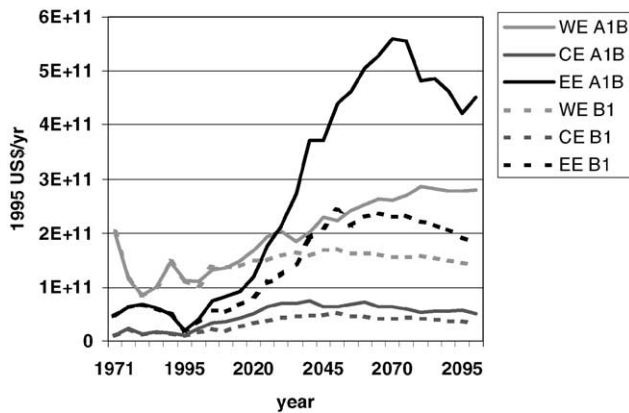


Fig. 10. The investments in the energy system (including annuitized energy efficiency investments) in OECD Europe, Eastern Europe and former USSR in the baseline and the mitigation scenarios.

the use of—in some regions cheap—indigenous fossil fuels, and the technology dynamics of non-carbon supply options.

The total *investment flows* into the energy system in the two scenarios and three regions are increasing with a factor 1.5–2.5 except for the former USSR where investments increase more than five-fold to sustain the high oil and gas export (Fig. 10). As a fraction of GDP, however, the energy system investments are constant or decline. However, there will be socio-political problems as there are winners and losers—for instance, in the B1 future the coal industry will rapidly decline and there are large opportunities for energy-efficiency and non-fossil oriented businesses. The

self-sufficiency ratio, defined as the ratio of energy produced and energy used in the region is shown for OECD Europe and the former USSR in Fig. 11. It is seen that OECD Europe will in all scenarios remain dependent for 30–50% on imported fuels. The former USSR, on the other hand, is projected to become a major exporter. The role of non-fossil supply options is increasing in all four scenarios, as Fig. 8 shows for the total of the three regions. In the baseline scenarios, where it slowly increases to over 40% in the form of wind, solar, nuclear, biomass and more hydropower, the driving force is a combination of fossil fuel depletion and cost decreases in the non-carbon options. In the mitigation scenarios, these same trends are accelerated as a consequence of the applied carbon taxes: all non-carbon supply options are introduced more rapidly and deeply.

Generally speaking, the two mitigation scenarios A1-550 and B1-450 differ from the baseline scenarios mainly in the faster and deeper penetration of energy-efficiency and non-zero carbon options. When after a few decades the cheap energy-efficiency and fuel substitution options are depleted, the role of renewable energy sources start to dominate. Already in the B1 scenario the improvement of both energy and carbon intensity reach levels at the higher end of the historical range—in agreement with the story line of the scenario. In the two mitigation scenarios, these improvement rates have to be even higher—which appears technically feasible but politically and institutionally a huge challenge (IPCC, 2001). Technological change will in any case play an important role; it stabilizes the initially rising marginal carbon abatement costs. Reduced investments in fossil fuels in the mitigation scenarios will imply less income for energy-exporting countries and energy companies.

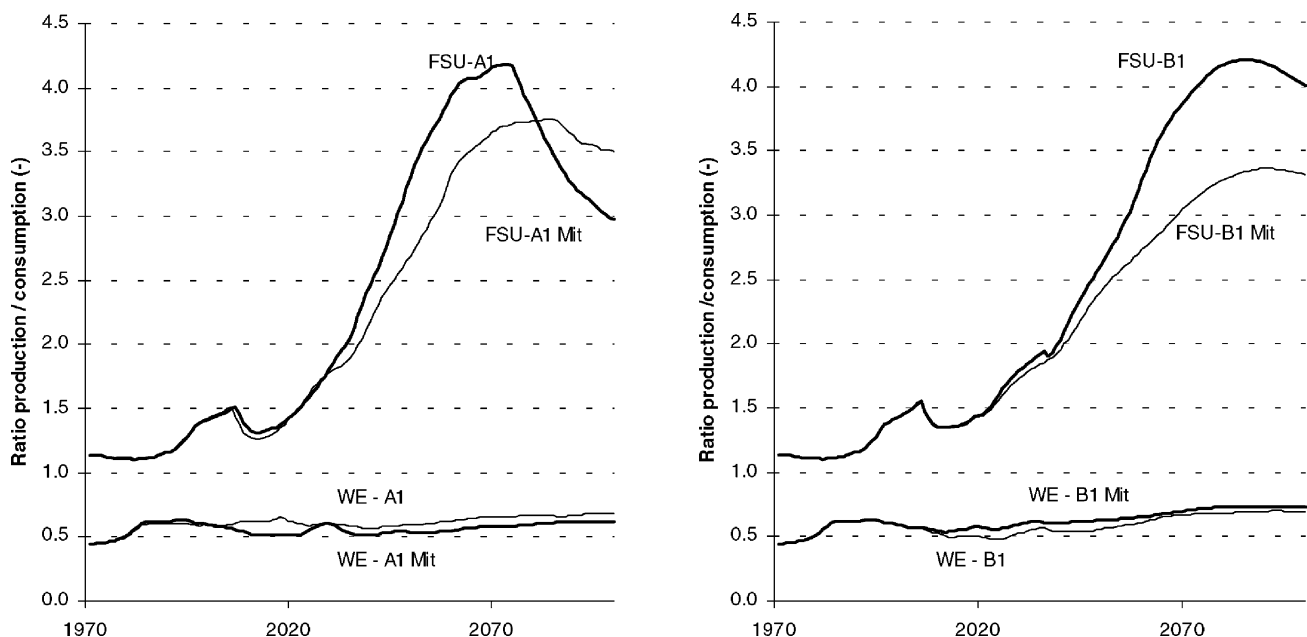


Fig. 11. Fuel trade measured as the ratio of production and consumption of fossil fuels and biomass-derived fuels in OECD Europe and the Former USSR.

The Middle East region, and later on the former USSR, will experience a lower growth in oil sales, although in absolute terms export earnings still rise significantly. It should be noted that the ‘carbon tax’ mitigation scenarios presented here presume that many of the required investments and skills are realized in the context of aid, trade and transfer interactions and such instruments as emission trading or Clean Development Mechanisms (van Vuuren and de Vries, 2001).

5. Greenhouse gas emissions

5.1. From energy use and industrial processes

In the B1 scenario *global CO₂ emissions* increase from 6 GtC in 1995–1911 GtC in 2040 after which they decline to 5 GtC in 2100. In the A1 scenario CO₂ emissions peak at the much higher level of 19 GtC in 2060 after which they go down to 15 GtC by 2100. In the B1-450 mitigation scenario emissions are reduced to 5.6 GtC in 2050, down to 2.2 GtC in 2100 for the world at large. For the A1-550 scenario, the equivalent values are 7.5 and 5.7 GtC.

Fig. 12 shows the energy- and industrial CO₂-emissions in the three European regions for the two baseline and the two CO₂ mitigation scenarios. It is seen that in the A1 future, the carbon emissions in the three European regions increase from about 1.9 GtC in 1990 to about 3.3 GtC by 2030 after which they start declining as the rising prices induce investments in energy-efficiency and non-carbon options. This is most pronounced in Eastern Europe where fast economic recovery is the major cause. The lower economic growth in combination with the orientation on sustainable development leads to lower carbon emissions in the B1 scenario: they peak before 2025 at a level of about 2.3 GtC per year. In the mitigation scenarios all three regions have significantly lower carbon emissions, as is to be expected. It should be noted that these reductions are the result of a uniform carbon tax; the resulting trajectories may be least-cost from an energy systems perspective but not from a wider economic and/or political perspective.

The CH₄ emissions from fossil fuel combustion, primarily from coal mining and gas venting in the former USSR show a similar pattern as that of the CO₂ emissions. In the A1 scenario there is first an increase to almost twice the 1990-level by 2020, and then a slow decline below the present levels. For the B1 scenario, the CH₄-emissions slightly increase, and then sharply decrease below the 1995-levels by 2050 (Fig. 12).

In the two mitigation scenarios, methane emissions are significantly lower than in the baseline due to less coal use and the introduction of abatement measures in coal and natural gas production and transport processes. Reduction of CH₄ emissions is thus an important part of an over-all strategy to reduce the risks of global warming.

5.2. Total

Energy use and industrial processes are not the only sources of greenhouse gas emissions. Other sources are (to quote only a few examples) CO₂ emissions from land-cover changes, CH₄ emissions from wetland rice fields, animals (enteric fermentation) and animal waste, landfills, and natural wetlands, and N₂O emissions from agricultural and natural soils. These emissions are calculated by two sub-models of IMAGE. The *Terrestrial Carbon* model computes the carbon fluxes between the atmosphere and biosphere as altered by CO₂ concentrations, climate change and various land cover conversions. Thereby the model keeps track in time and space of all major pools and fluxes of carbon in the terrestrial environment (Klein Goldewijk et al., 1994). The *Land Use Emissions* model calculates the emissions of different greenhouse gases and ozone precursors stemming from land use and biotic sources (Kreileman and Bouwman, 1994). These emissions are not changing in the two mitigation scenarios as we have not considered any changes in land cover or reduction measures regarding land use related greenhouse gas emissions.

Fig. 13 shows the development of the global CO₂ equivalent emissions from energy use, industrial processes and land-use. While for the A1 scenarios the emissions increase up to 31 GtC in 2050 and slowly decline after 2060, for the B1 scenarios the maximum emissions (around 2030) are about 10 GtC lower. In 2100 the emissions in the B1 scenarios will have declined to 1990 levels (ca. 12.5 GtC) and in the B1-450 scenarios to about 9.6 GtC.

For the mitigation scenarios developed by TIMER it was assumed that also some action is taken in the field of mitigating land use emissions. However, the runs included in this paper do not include mitigation of CO₂ from land-use sources. Therefore, the computed CO₂ concentrations in 2100 are slightly higher than 450 and 550 ppmv, respectively.

6. Air pollution emissions

6.1. SO₂ and NO_x

In the scenarios with the present air pollution policies the emissions reach the Gothenburg levels in 2010, afterwards the achieved reduction level is kept constant, i.e. there is no further reduction effort. However, due to changes in the driving forces (population, GDP, technology) there is a continuous change in the energy use and the energy carrier mix resulting in changing unmitigated SO₂ and NO_x emissions. The overall result is that even with a constant reduction level the emissions further decline. In addition, for the A1-P and the B1-P scenarios the emissions have to be capped at the Gothenburg level for some time (longest for NO_x emissions of A1-P), i.e. the reduction level of 2010 is by itself not sufficient to keep the emissions below the Gothenburg level and additional short-term measures are necessary (see Fig. 14).

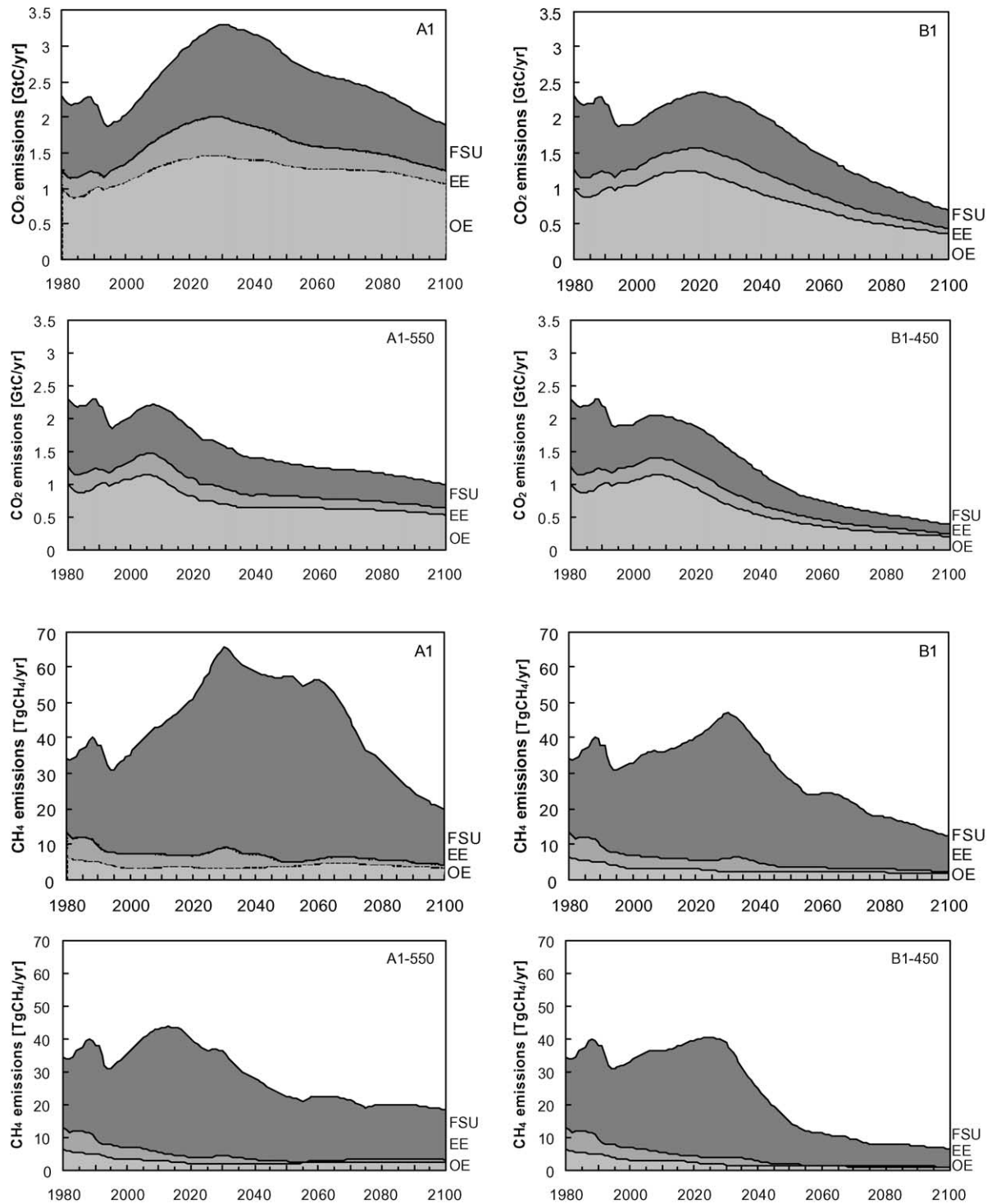
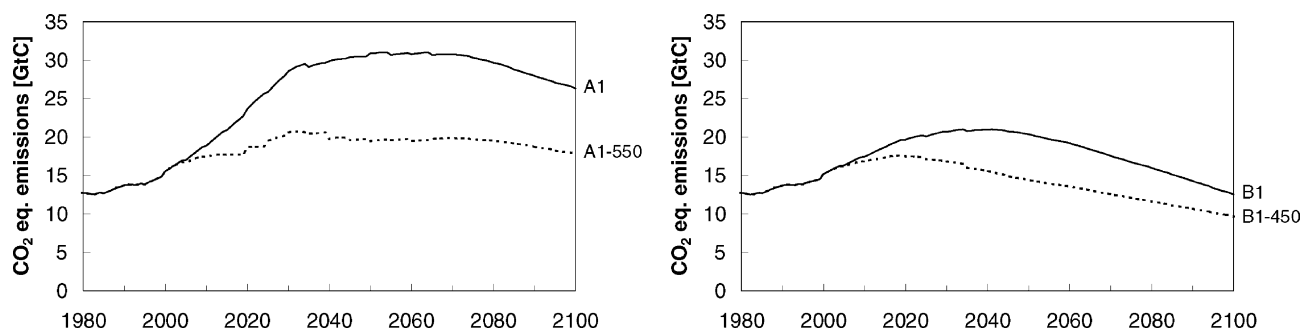
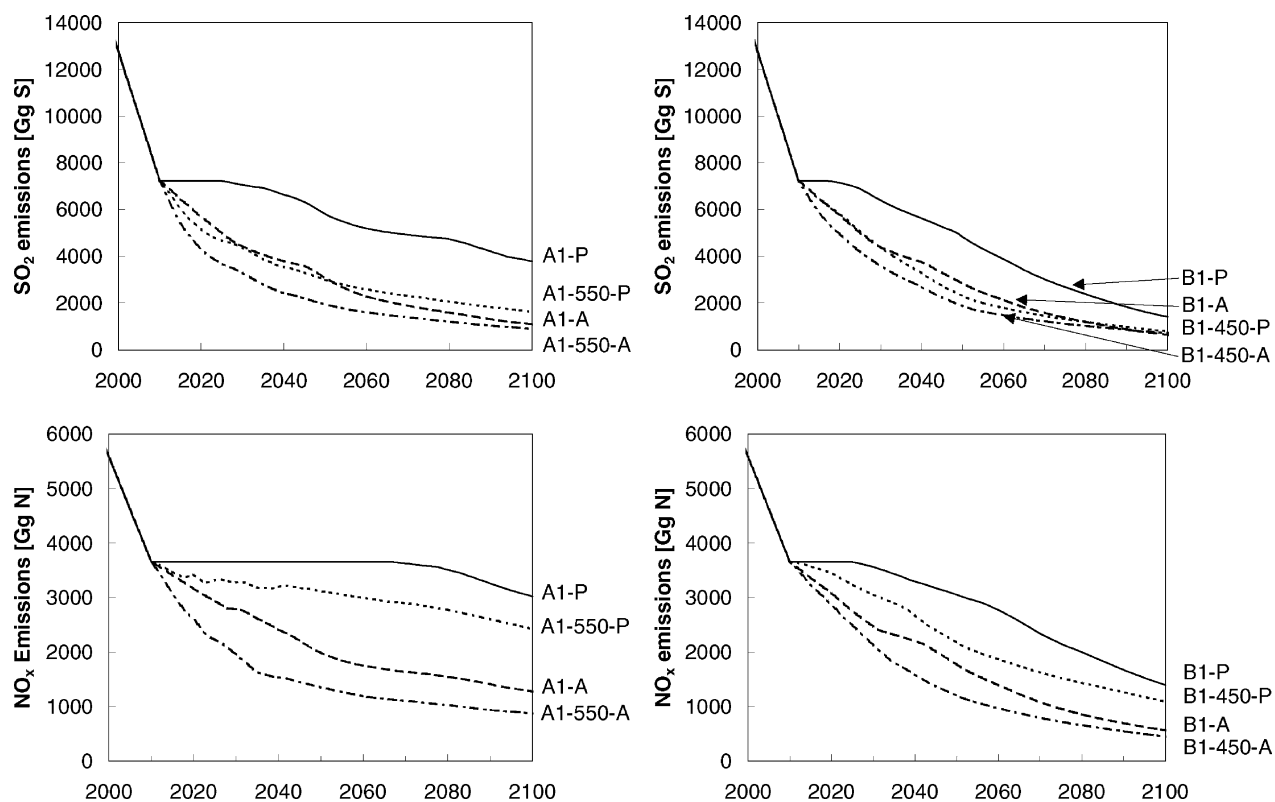
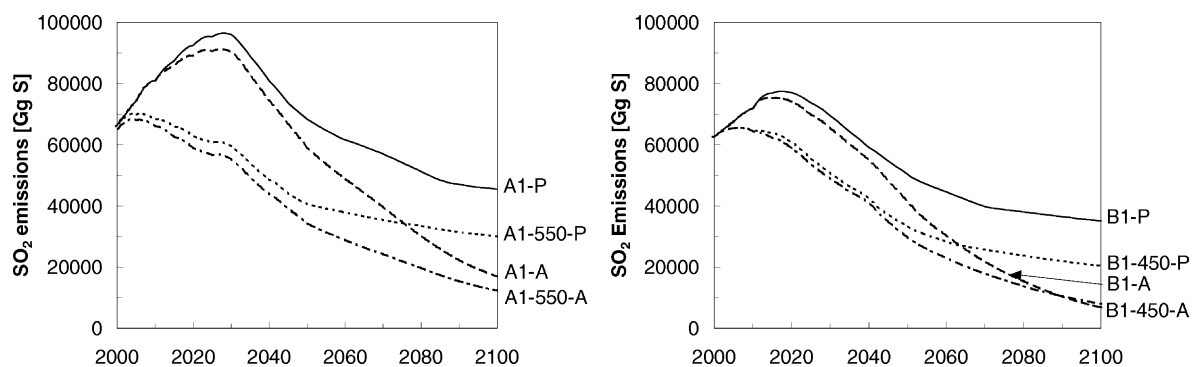


Fig. 12. The energy- and industrial emissions of CO₂ and CH₄ (left-hand side A1 world, right-hand side B1 world) (OE: OECD Europe, EE: East Europe, FSU: former USSR).

The climate policies by themselves already succeed in mitigating the SO₂ emissions considerably while they may help to comply with the Gothenburg levels for NO_x. In both the A1 and B1 world, however, the most significant reductions are already accomplished by 2010. Interestingly

in Europe the SO₂ emissions and the NO_x emissions in the B1 world tend to converge in 2100.

For the scenarios without climate policy (e.g. A1-P, A1-A) the resulting global SO₂ emissions peak around 2030 (A1 world) and 2020 (B1 world), respectively, and then decline

Fig. 13. Global CO₂ equivalent emissions (including land-use emissions).Fig. 14. SO₂ and NO_x emissions in Europe (left-hand side A1 world, right-hand side B1 world).Fig. 15. Global SO₂ emissions (left-hand side A1 world, right-hand side B1 world).

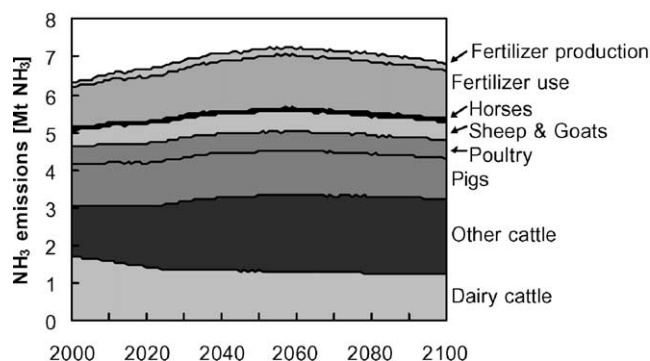


Fig. 16. NH_3 emissions in Europe per source for the A1-P scenario.

significantly (see Fig. 15). The impacts of sulfur on climate (cooling effect) will decrease after 2030 accordingly. The decline already manifests in the unmitigated emissions (i.e. it is a result of the driving forces), after adding either the present or the advanced air pollution policy the decline is only more marked. The explanation for this is that the A1 and B1 scenarios are scenarios with high economic growth. The scenarios assume that part of this wealth is invested in improving health and the environment leading to a shift in the energy mix and thus in a decline of the unmitigated SO_2 emissions.

For the scenarios with climate policy (e.g. A1-550-P, A1-550-A) the peak about 2020/2030 is avoided. The global emissions hardly rise above the 1990 levels. It is of interest to note that the global SO_2 emissions in 2100 converge for the scenarios with advanced air pollution policies (e.g. A1-A and A1-550-A) i.e. in the long-term the climate policies hardly have any additional effect in this respect.

6.2. NH_3

The assumed climate policies do not affect livestock numbers or fertilizer production and use. Furthermore for NH_3 no air pollution policies are assumed. Thus, NH_3 emissions

do differ between the A1 and the B1 world, but not from one scenario to another within one of these worlds. For the A1 scenarios the total European NH_3 emissions vary only slightly for the next 100 years (6.9 Mt NH_3 in 2100) while for the B1 scenarios the emissions steadily decline after 2020 to 4.1 Mt NH_3 in 2100. Cattle husbandry (for milk and meat production) is the most significant source, followed by fertilizer use and pigs husbandry (see Fig. 16).

7. Climate change

7.1. Temperature and precipitation

In the IMAGE 2.1 climate model the effects of sulfate aerosols is modeled following the approach of Charlson et al. (1992). The distribution of sulfate aerosols is computed from the regional SO_2 emissions with a linear source-receptor matrix derived from a two-dimensional global model of atmospheric chemistry (Alcamo et al., 1998b). The practically instantaneous cooling effect of SO_2 emissions on climate is of special interest in this study. A comparison of the calculated global temperature of the scenarios with present air pollution policies to those with advanced air pollution policies showed that a decrease of the global SO_2 emissions of 50 TgS results in an increase of the global temperature in that year of about 0.05–0.2 K. Thereby, the size of the effect as well as the regional temperature changes depend on the regional distribution of the emissions.

For A1-P the increase in global average surface temperature between 1990 and 2100 resulting from the buildup of the greenhouse gases is 2.7 K (Fig. 17). The difference between present and advanced air pollution policies on this parameter is small: for A1-A the temperature increase is 2.8 K, i.e. 0.1 K higher. For the A1 scenarios with climate policy the global temperature increases only up to 1.9 K (A1-550-A) and 2.0 K (A1-550-P), respectively. In the B1 world the temperature changes are considerably lower: 1.5 and 1.6 K for the scenarios without climate policy and 1.0

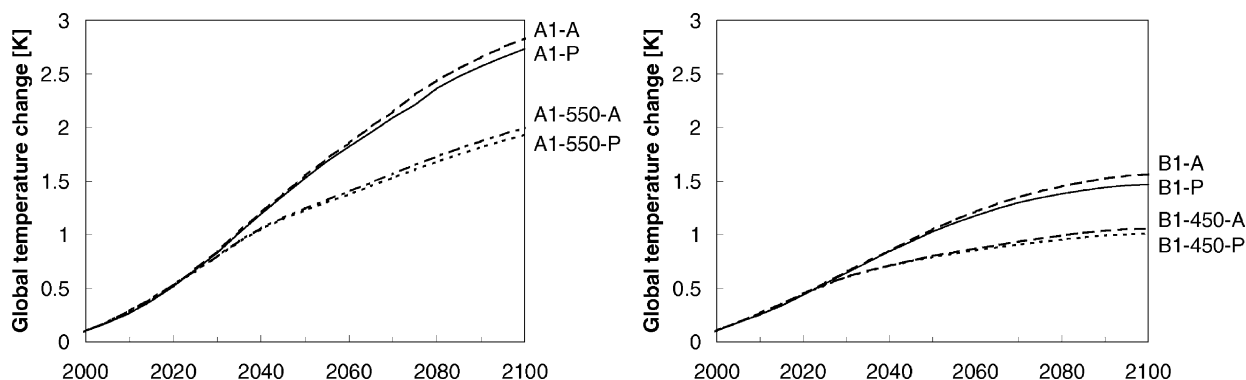


Fig. 17. Increase in global average surface temperature relative to 1990.

and 1.1 K for the scenarios with climate policy. These calculations are based on a climate sensitivity (i.e. the long-term or equilibrium temperature change following a doubling of CO₂ equivalent concentrations) of 2.4 K, which is close to the generally accepted best estimate of 2.5 K (with a range of 1.5–4.5 K).

For Europe the average temperature change will be considerably higher than the world average under the no-climate-policy scenarios: relative to 1990 the temperature will increase by 3.4 and 3.3 K for the A1-A and A1-P scenario, respectively. The greenhouse gas emissions of the B1 world lead to an average temperature change of 1.8 (B1-A) and 1.7 K (B1-P) in Europe. As our calculations show, Europe will considerably profit from global climate protection measures: under the A1-550 scenarios tempera-

ture change will be lowered by about 1.0 K whereas under the B1-450 scenarios temperature increase is about 0.5 K lower compared to the no climate-policy scenarios.

Beside temperature increase the change of precipitation is a key impact of climate change. The most severe precipitation changes we found for the Scandinavian countries and for Spain, although in opposite directions. Scandinavia will face almost a doubling of precipitation under the A1-P scenario in 2100 whereas the Iberian Peninsula will have to bear a substantial decrease of precipitation up to around 30% (or less) of current levels. Central Europe, i.e. Germany, Poland and Belarus will see only minor changes in the annual precipitation. However, this does not exclude a change of seasonal patterns. For the other emission scenarios we found the same patterns for precipitation change but less marked

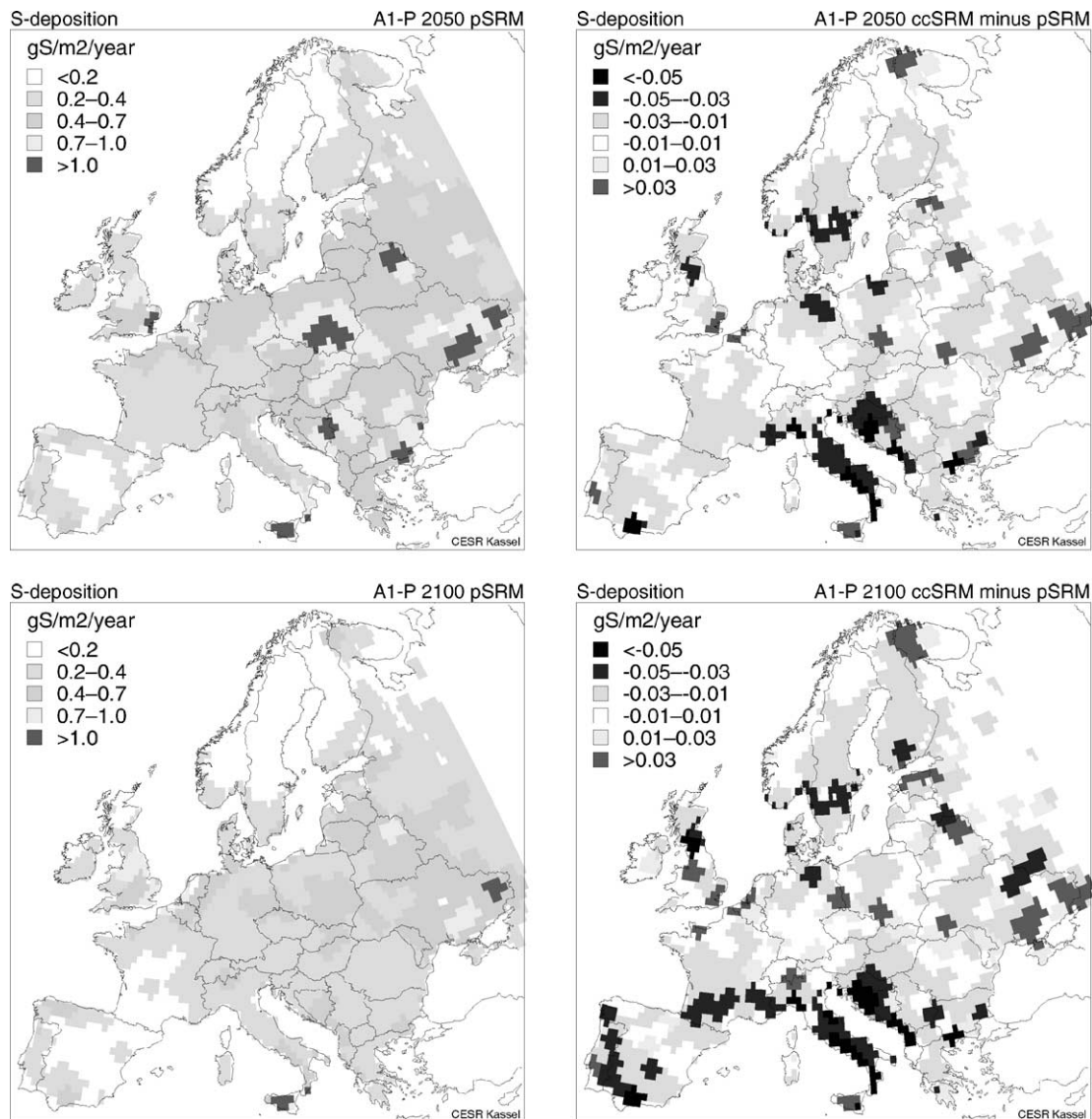


Fig. 18. Sulfur deposition for the years 2050 and 2100 under the A1-P scenarios, using the present SRMs (pSRM) (left-hand side) and the difference when using the climate-changed SRMs (ccSRM) (right-hand side).

increases or decreases. It should be kept in mind, however, that patterns of precipitation change can considerably differ depending on the GCM used for the calculations. Further details on the European climate are given by van Minnen et al. (2001).

8. Change in air pollution

Air pollution is calculated with the present SRMs (see Section 2.5.1) using the European SO_2 , NO_x and NH_3 emissions outlined in Section 6. In 2010 the emissions are for all scenarios at the levels specified in the Gothenburg Protocol (UN-ECE, 1999). The resulting sulfur deposition is $<1.5 \text{ gS/m}^2$ per year nearly everywhere in Europe.

For comparison: in the early 1980s the S deposition was $>10 \text{ gS/m}^2$ per year in parts of central Europe. For the A1-P scenario the sulfur deposition declines to $<0.7 \text{ gS/m}^2$ per year in 2100 (Fig. 18). Two peaks remain: one is in the Donbas region in the east of the Ukraine that has at present the highest emissions in Europe. The other remaining peak is in Sicily and is due to the (natural) emissions of Mount Etna.

For B1-450-A, the scenario with the lowest SO_2 emissions in Europe, the S deposition drops nearly everywhere $<0.6 \text{ gS/m}^2$ per year already in 2050 (even $<0.2 \text{ gS/m}^2$ per year in most of the European Union) and to $<0.2 \text{ gS/m}^2$ per year in 2100. The S deposition in coastal regions (e.g. along the Channel and along the German and Danish coast to the North Sea) is slightly higher because of the shipping

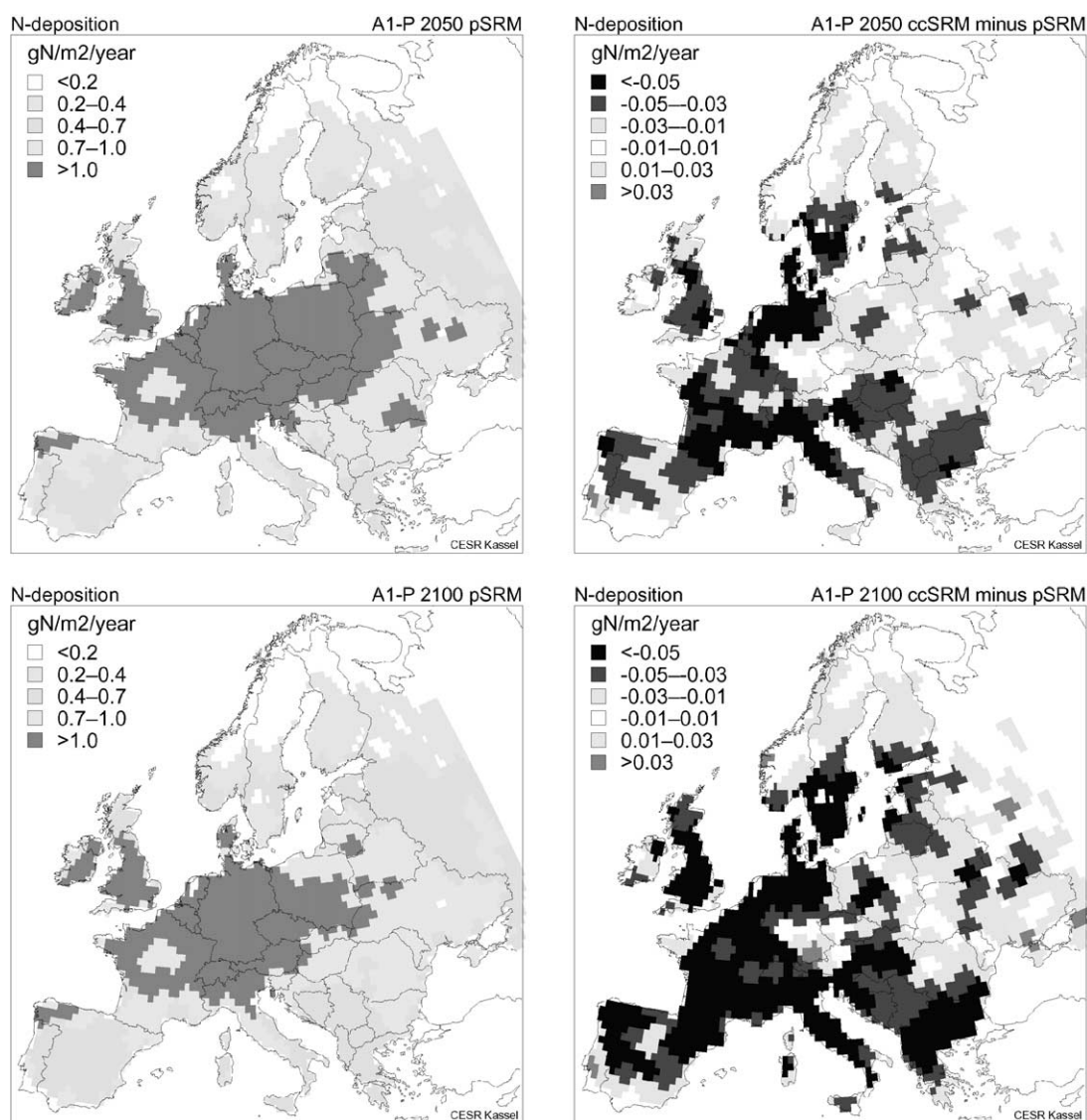


Fig. 19. Nitrogen deposition for the years 2050 and 2100 under the A1-P scenarios, using the present SRMs (pSRM) (left-hand side) and the difference when using the climate-changed SRMs (ccSRM) (right-hand side).

emissions. As there are no international reduction agreements on shipping emissions they have been assumed to stay at the present levels.

The nitrogen deposition in 2010 is in most parts of Europe comparable or markedly higher than the sulfur deposition (also on an equivalence basis), thus, emphasizing the growing importance of nitrogen compared to sulfur. As the NO_x emissions scarcely decrease for A1-P, the picture is hardly changed by 2100 (Fig. 19). Even for B1-450-A the N deposition remains $>1.4 \text{ gN/m}^2$ per year in some areas with intensive agro-industrial activities (e.g. The Netherlands) and $>0.6 \text{ gN/m}^2$ per year in most of central Europe.

With the climate-changed SRMs (interpolated as described in Section 2.5.2) sulfur and nitrogen deposition were calculated for A1-P in 2050 and 2100. Figs. 18 and 19 show the differences between these results and the results calculated with the present SRMs. They are mostly $<0.03 \text{ gS}$ or gN/m^2 and year, i.e. small in comparison to the absolute deposition values. The calculated deposition is almost everywhere in Europe lower when taking the influence of climate change on dispersion and chemical transformation of pollutants into account, for nitrogen even more so than for sulfur. As climate change (and thus change in weather patterns) is large for the A1-P scenario (only for A1-A it is slightly larger) it can be concluded for these limited model experiments that changes in emissions will have a considerably larger effect on deposition in Europe than changes in weather patterns due to climate change.

9. Main findings and conclusions

In the AIR-CLIM project an integrated modeling framework was successfully developed that allows to analyze the linkage between climate change and regional air pollution in Europe. The framework integrates state-of-the-art models and concepts from the area of climate change and regional air pollution and was supplemented by new modules (e.g. modeling long-term NH_3 emissions in Europe, modeling dispersion and transformation of air pollutants under climate change). One unresolved point is how to disaggregate consistently regional European emissions to country emissions after 2010.

Among other things, the framework was used to develop and analyze integrated scenarios for climate change and regional air pollution. Two differing storylines on how the future world could develop under certain circumstances were combined with various climate policies and air pollution policies to identify and evaluate comprehensive policy strategies for controlling both environmental issues simultaneously. Thereby, both the climate and the air pollution policies were driven by the desire to achieve certain environmental goals or—to put it differently—to avoid (larger) environmental damages. Costs played only a secondary role

in the definition of the policies. Instead costs are end-points of the analysis to be compared with the remaining impacts (see Alcamo et al., 2002).

The following conclusions can be drawn from the analysis of emissions, climate change and regional air pollution:

- **Energy use:** Climate policy measures as simulated by a uniform carbon tax would induce a set of measures which could stabilize CO_2 concentrations at levels of 450–550 ppmv by 2100. Thereby, carbon tax is a proxy of the sum of mitigation policies focusing on the energy system. Non-energy-related mitigation options (e.g. afforestation, CO_2 disposal) are not considered. The result is that in the greenhouse gas mitigation scenarios energy-efficiency and non-zero carbon options are introduced faster and penetrate more than without. When after a few decades the cheap energy-efficiency and fuel substitution options are depleted, the role of renewable energy sources start to dominate.
- **Greenhouse gas emissions:** In the baseline scenarios greenhouse gas emissions will keep growing over the next two to three decades, thereafter they start to decline slowly as low/zero-carbon options become more competitive. Thereby, because of its focus on sustainability the maximum emission increase relative to 2000 is for the B1 world only about half that of the A1 world. For the A1 world the uniform carbon tax succeeds in keeping the emissions at about the level of 2000 while for the B1 world the emissions decline earlier and faster than for the baseline. The emission pathways of the three European regions for the baseline and the mitigation scenarios are analogous to the world-wide trend.

The CH_4 emissions of the former USSR are much higher than for OECD Europe and Eastern Europe. The reduction of CH_4 emissions would be an important part of an over-all mitigation strategy for Europe.

- **SO_2 and NO_x emissions in Europe:** Due to the continuous change in energy use and in the energy carrier mix the European SO_2 and NO_x emissions decline for the baseline scenarios even without further application of end-of-pipe-technologies. However, this decline is not sufficient to keep the emissions below the emission caps specified in the Gothenburg Protocol within the A1 world. To achieve this objective throughout the 21st century, the end-of-pipe reduction rate of 2010 is not sufficient, additional short-term measures are necessary.

Even if the past trend of the end-of-pipe reduction rate is extended for the next hundred years (here called advanced air pollution policy), the resulting additional reductions are significantly lower than those already accomplished by 2010. For SO_2 the climate policies by themselves already succeed in mitigating the SO_2 emissions considerably while helping to comply significantly with the Gothenburg levels for NO_x . Interestingly, in the long-term it hardly makes a difference for the SO_2

emissions whether only the air pollution policy or the climate policy or both policies are applied.

- *Global SO₂ emissions:* For the scenarios without climate policy the global SO₂ emissions peak around 2020–2030 and then decline significantly because of the decline in energy use per capita and because of the shift to initially gas and later non-thermal options. For the scenarios with climate policy the peak is avoided and the global emissions hardly rise above the 1990 levels.

In the short-term (up to 2050) the air pollution policies have hardly any effect on the global emissions. In the long-term, however, they become more effective in reducing the emissions than the climate policy.

- *Climate change:* For the baseline scenarios the global mean temperature in 2100 is 2.7 K (A1) or 1.5 K (B1) higher than in 1990. The temperature increase is much lower for the greenhouse gas mitigation scenarios: 2.0 K in the A1 world for a CO₂ concentration of 550 ppmv in 2100, and 1.1 K in the B1 world for 450 ppmv CO₂. Europe will see a higher temperature change than the global average as well as increasing precipitation in Scandinavia and in part substantially decreases of precipitation in the Iberian Peninsula.
- *Impact of SO₂ on climate change:* The effect of the air pollution policies on the global mean temperature is minor: contrary to earlier studies, only a small effect of SO₂ emissions on climate change in 2100 is calculated. The reason for this is the decrease of the (global) SO₂ emissions to 1990 levels or lower while former studies assumed a continuing increase.
- *Air pollution in Europe:* Even without a policy beyond the Gothenburg Protocol the sulfur deposition will fall <1.5 gS/m² per year nearly everywhere in Europe. For comparison: in the early 1980s the sulfur deposition was in parts of central Europe >10 gS/m² per year. The S deposition in coastal regions is slightly higher because of the shipping emissions for which so far there are no international reduction agreements.

The picture is different for nitrogen deposition. After the Gothenburg Protocol is implemented the nitrogen deposition is markedly higher than the sulfur deposition, thus emphasizing the growing importance of nitrogen compared to sulfur. Even for the scenarios with both climate and air pollution policies that have the lowest long-term NO_x emissions the nitrogen deposition remains >0.6 gN/m² per year in most of central Europe and even >1.4 gN/m² per year in some areas with intensive

agro-industrial activities (also due to the NH₃ emissions for which no mitigation measures have been assumed here).

- *Impact of climate change on regional air pollution:* In the above results, the impact of climate change via changed weather patterns on regional air pollution was not taken into account. However, a sensitivity analysis based on calculations with the EMEP Lagrangian Acid Deposition Model (LADM) using output from a climate model showed that the effect is probably minor. The changes in emissions will have a considerably larger effect on deposition in Europe than changes in weather patterns due to climate change. These results are, however, based on LADM runs for the output of one climate model. It might be that with the output of another climate model the results might be different as climate models, while agreeing rather well with respect to global mean temperature, differ considerably for precipitation and for regional climate.

Thus, according to this part of the analysis within AIR-CLIM the quantitatively most relevant interactions are the effect of climate change policies on the energy mix and the resulting air pollution emissions. In the long-term the global SO₂ emissions are expected to decrease (again), thus their effect on climate will be minor. Tentatively it can be concluded that for regional air pollution the development of the emissions of air pollutants is more important than the effect of climate change on the dispersion and chemical transformation of air pollutants.

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Appendix A

A.1. Timer

Regions	Sectors	Primary energy carriers
1 Canada	1 Industry	1 Coal
2 USA	2 Transport	2 Heavy liquid fuel (from oil)
3 Central America	3 Residential	3 Light liquid fuel (from oil)
4 South America	4 Services	4 Gas (natural gas or from oil or coal)
5 Northern Africa	5 Other	5 Modern biofuel
6 Western Africa		6 Traditional biofuel
7 Eastern Africa		7 Non-thermal electricity (wind, solar, nuclear, etc.)
8 Southern Africa		8 Hydropower
9 OECD Europe		
10 Eastern Europe		
11 Former USSR		
12 Middle East		
13 South Asia		
14 East Asia		
15 South East Asia		
16 Oceania		
17 Japan		

A.2. Image 2.1

Regions	Sectors	Food and energy crops
1 Canada	1 Industry	Food crops
2 USA	2 Transport	Temperate cereals
3 Latin America	3 Residential	Rice
4 Africa	4 Services	Maize
5 OECD Europe	5 Other	Tropical cereals
6 Eastern Europe		Pulses
7 Former USSR		Roots and tubers
8 Middle East		Oil crops
9 India plus South Asia		Biofuel crops
10 China plus centrally planned countries		Sugar cane
11 East Asia		Maize
12 Oceania		Woody biomass
13 Japan		Non-woody biomass
		Feed crops
		Grass and fodder species

OECD Europe consists of the 15 countries of the EU, Iceland, Norway, and Switzerland while East Europe comprises Albania, Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, and the former Yugoslavia. In [Alcamo \(1994, p. 33\)](#), the countries comprising other world regions in IMAGE are listed.

The 17 regions of TIMER correspond to the regions of the (up-coming) version 2.2 of IMAGE that was not available for this project. Accordingly the TIMER output on bio-fuel demand and emissions from energy use and industrial processes has to be converted to the 13 regions of IMAGE 2.1. Central and South America combined constitute Latin America of IMAGE 2.1, as Northern, Western, Eastern and Southern Africa do Africa. The Asian regions of the two regional disaggregations do not correspond in this way. For them, the TIMER output were converted based on the respective regional land areas as the simplest measure available. The results presented in this paper for land cover changes and impacts in Europe are hardly affected by the resulting error. For the calculation of European air pollution only the emissions of the European part of the former USSR have been taken into account. The emissions of the former USSR have been divided into emissions in the Asian and in the European part based on the distribution in 1990 according to the GEIA database ([Benkovitz et al., 1996](#)).

Appendix B

To apply the SRMs for the two timeslices in the AIR-CLIM project they have to be interpolated for different scenarios and years. The average temperature in the EMEP area is used to linearly interpolate the SRMs between the future and the control period to calculate the SRM $M_{S,Y}$ for a specific scenario S and year Y. In addition, $M_{S,Y}$ is normalized in such a way that for 1990 the result is the present SRM. Accordingly, the interpolation formula is as

follows:

$$M_{S,Y} = M_{AM} \frac{w_{S,Y} M_{FP} + (1 - w_{S,Y}) M_{CP}}{w_{AM} M_{FP} + (1 - w_{AM}) M_{CP}} \quad (B.1)$$

where

$$w_{S,Y} = \frac{T_{S,Y} - T_{1970s}}{\Delta T_{TSE}} \quad (B.2)$$

and M_{CP} is the country-to-grid matrix for ECHAM4 meteorology for control period (1971–1980); M_{FP} the country-to-grid matrix for ECHAM4 meteorology for IS95a scenario future period (2041–2050); M_{AM} the country-to-grid matrix for actual meteorology (1986–1996); ΔT_{TSE} the difference in average temperature in EMEP area between future and control period for ECHAM4 meteorology (2.7 K); $T_{S,Y}$ the average temperature in EMEP area calculated by IMAGE 2.1.2 for scenario S and year Y; T_{1970s} the average temperature in EMEP area calculated by IMAGE for the 1970s (6.5 K); w_{AM} the normalization factor, chosen so that for 1990 the country-to-grid matrix for actual meteorology is calculated (0.2/2.7).

Other extrapolation formulas (e.g. exponential functions) are possible but would not yield significant different results within the time-frame of the scenarios.

Appendix C

Scenario assumptions for TIMER energy model. The assumptions for the different energy scenarios in the TIMER model were based on the corresponding marker scenarios as published by IPCC ([Nakicenovic et al., 2000](#)) and their story lines. For the mitigation scenarios the same assumptions are used; however, a carbon tax is introduced (see text) which induces a variety of responses. [Table 5](#) summarizes the various assumptions; [Table 6](#) provides explanatory notes.

Table 5

Assumptions made in deriving the baseline scenarios A1 and B1 and the greenhouse gas mitigation scenarios A1-550 and B1-450

Source	Scenario	
	A1	B1
Demand side		
Energy tax levels	Energy end-use taxes for all sectors, regions and fuels converge towards a 2100 level equal to 1995 USA	Energy end-use taxes for all sectors, regions and fuels converge towards a 2100 level equal to 1995 OECD Europe
Structural change parameter	Reaches a value 55–70% above default value to reflect material intensive life-styles	Reaches a value 20% below default value to reflect transition towards less material-intensive lifestyles
Pay-back times	Reaches for all regions the current high-income region values (1.2–3.3 years, depending on sector)	Increases for all regions to levels twice the current high-income region values (2.75–6.2 years, depending on sector)
End-use conversion efficiency secondary fuels	Increases in both scenarios and all regions to a level of 80% for coal (85% for industry), 90% for oil, 94% for natural gas and 35% for traditional fuels (45% in industry). For electricity the conversion efficiency is set equal to 1.0	
Autonomous efficiency improvement (AEEI)	Faster in Eastern Europe and CIS once economic growth recovers, reflecting capital and technology transfer in open, liberalized world	Faster in Eastern Europe and CIS once economic growth recovers, reflecting capital and technology transfer in open, regulated world
Premium factors final energy carriers	Positive and increasing because of aversion from use of coal with rising income, for health, convenience and environmental reasons	
Learning coefficient for price-induced energy efficiency (PIEEI)	Modest learning, that is, reduction in US\$/GJ saved investment per doubling of investment 8% by 2100	Normal learning, that is, reduction in US\$/GJ saved investment per doubling of investment 10% by 2100
Supply side		
Resources for fossil fuels	Default values for fossil fuel resources and supply-cost curves have been used. These values and curves have been derived from (Rogner, 1997)	
Learning coefficient for coal (surface coal only)	Slow learning, that is, Capital-Output-Ratio declines per doubling of regional surface coal output 5%	
Learning coefficient for oil and gas	Normal learning, that is, Capital-Output-Ratio declines per doubling of regional oil and natural gas output respectively with 10%	
Learning coefficient for biofuels	Initially strong learning, that is, yield increases per doubling of BF output 12%	Initially strong learning, that is, yield increases per doubling of BF output with 10–15%
Electricity generation		
Learning coefficient for solar/wind	Initially strong learning, that is, specific investment costs declines per doubling of BF output with 9–15%	Initially strong learning, that is, increase in yield declines per doubling of BF output with 9–15%
Learning coefficient for nuclear	Initially strong learning, that is, specific investment costs declines per doubling of nuclear electricity 10% later 5%	Slow learning, that is, specific investment costs declines per doubling of nuclear electricity with 4%
Use of hydropower	Rather large expansion towards 81/60/30% of technical potential in OECD/Eastern/FSU	Expansion towards 80/50/20% of technical potential in OECD/Eastern/FSU
Premium values electricity sector	No preferences or aversion for any fuel in the 21st century: slowly declining to zero	Positive and increasing because of strong aversion from use for environmental reasons. Reaches factor 1.7 in all regions by 2100
Thermal efficiency electricity generation	Increase towards 49% (coal-fired), 54% (oil) and 58% (gas)	Increase at only slight increase in specific investment costs towards 48% (coal-fired), 53% (oil) and 57% (gas)

Table 5 (Continued)

Source	Scenario	
	A1	B1
Trade		
Trade constraints	All import and exports constraints are removed	
Transport costs	Decreasing for natural gas in all regions with 20%; constant for other fuels	
Emissions		
Carbon dioxide (CO ₂)	Constant fuel-dependent emissions factors. Industrial production trend extrapolation for feedstocks and cement	
Methane (CH ₄)	Constant fuel-dependent emissions factors. In fuel production, up to 15% emission reduction and/or decrease to OECD level over the period 2025–2045	
Nitrous oxide (N ₂ O)	Constant fuel-dependent emissions factors. In transport sector existing environmental NO _x policy. For nitric acid production all plants towards 80–100% reduction by 2050–2100	As in A1. In transport 15 years earlier convergence in reduction
Carbon monoxide (CO) and NMVOC	Constant fuel-dependent emissions factors. In transport convergent reductions across regions to 35% reduction targets	Constant fuel-dependent emissions factors. In transport convergent reductions across regions to 35% reduction targets, but slightly faster than in A1
Nitrogen oxides (NO _x)	Constant fuel-dependent emissions factors	Constant fuel-dependent emissions factors
Sulfur oxides (SO ₂)	Present sulfur policy until 2010, after 2010 as in B1 but with 25 year delay. In FGD and desulfurization convergence in policies and reduction fractions	Present sulfur policy until 2010, after 2010 further reduction towards 80–90% by 2020–2030 with regional convergence. In FGD and desulfurization convergence in policies and reduction fractions

Table 6
Explanatory notes on the AIR-CLIM scenarios

Parameter	Explanatory notes
Demand side	
Energy tax levels	In the model, for all sectors, regions and fuels time-dependent energy taxes are added to the end-use prices. The taxes are added in terms of US\$/GJ and are, in general, higher for electricity and transport fuels
Structural change parameter	Energy demand is calculated by first estimating the demand for energy services based on monetary activity indicators per sector. The relation between the demand for energy services and the monetary activity indicator is assumed to change of time as result of <i>structural change</i> , e.g. changes in modal split in transport or shifts from heavy to light industry in the sector industry
End-use conversion efficiency secondary fuels	In the conversion between the demand for energy services and final energy use end-use conversion efficiencies play an important role. In TIMER, these fuel, sector and time-dependent efficiencies are included as exogenous scenario files
Autonomous efficiency improvement (AEEI)	Autonomous efficiency improvement captures the increasing efficiency between the demand for energy services and the demand for final energy caused by price-independent technology development. Estimates of the historic importance of this parameter vis-à-vis price-induced energy efficiency improvement or structural change differ strongly—medium estimates are around 0–0.5% per year
Technology learning rate for price-induced energy efficiency (PIEEI)	Energy efficiency investments tend to become most cost-effective in time due to technological development. As for other technologies, in TIMER technology development for energy efficiency is modeled by a ‘learning curve’. The actual rate of learning is a function of initial settings (assumptions about cumulative output before starting year of the simulation) and the progress ratio (1—reduction of costs for a doubling of cumulative output)
Premium factors final energy carriers	The end-use fuels ‘solid fuels’, ‘liquid fuels’ and ‘gaseous fuels’ compete for market share on the basis of their relative prices and an additional premium value (in some cases, mostly historically, sectors are shielded for penetration of certain fuels). These premium values capture other factors that determine market shares of fuels, in particular consumer preferences and environmental policies
Supply side	
Resources for fossil fuels	In TIMER depletion of fossil fuels is given in terms of supply-costs curves (assuming constant technology). For all fuels, these curves have been derived from a publication of Rogner (1997). The curves do not only include currently known reserves and conventional occurrences but also estimates for non-discovered and unconventional occurrences (e.g. methane hydrates and tar sands)
Technology learning rate for coal (surface coal only)	As for other technologies, in TIMER technology development in terms of the production costs for surface coal is modeled by a ‘learning curve’. The actual rate of learning is a function of initial settings (assumptions about cumulative output before starting year of the simulation) and the progress ratio (1—reduction of costs for a doubling of cumulative output)
Technology learning rate for oil and natural gas	See above. In literature often progress ratios between 0.8 and 0.95 are reported. In TIMER most curves have been calibrated in such way that 0.9 is considered to be reasonable default value. For oil the historic progress ratio is set at different values for different regions—but tend to converge around 0.9. Progress ratios can vary in time
Technology learning rate for biofuels	See above. In literature often progress ratios between 0.8 and 0.95 are reported. In TIMER most curves have been calibrated in such way that 0.9 is considered to be reasonable default value. For biofuels the historic progress ratio is around 0.88. Progress ratios can vary in time
Electricity generation	
Technology learning rate for solar/wind	See above. In literature often progress ratios between 0.8 and 0.95 are reported. In TIMER most curves have been calibrated in such way that 0.9 is considered to be reasonable default value. For solar/wind the historic progress ratio is set at 0.85. Progress ratios can vary in time
Technology learning rate for nuclear	See above. In literature often progress ratios between 0.8 and 0.95 are reported. In TIMER most curves have been calibrated in such way that 0.9 is considered to be reasonable default value. For nuclear power the historic progress ratio is set at average at 1.0 (as additional environmental and risk related conditions for nuclear power have offset costs reductions due to improved technology). Progress ratios can vary in time
Use of hydropower	The use of hydropower in TIMER is determined by two exogenous scenario files: (1) the share of the technical potential per region actually used for hydropower capacity and (2) the load factor of this capacity
Premium values electricity sector	The use of the different fuel types for electricity generation in thermal power plants is determined their relative prices, the efficiency with which these fuels can be used and an additional premium value. These premium values capture other factors that determine market shares of fuels, in particular environmental policies and strategic considerations. If no preference or aversion for a certain fuel type exists, the premium value is set at 1. In most TIMER scenarios in particular premium values for are raised in certain scenarios to reflect environmental considerations
Thermal efficiency electricity generation	An important parameter in thermal electricity generation is the efficiency by which primary fuels are converted into electricity. These efficiencies are a function of time, region and fuel type. The efficiencies can change over time, among others as result of technology development, additional environmental technologies, etc.

Table 6 (Continued)

Parameter	Explanatory notes
Trade	
Trade constraints	All regions in TIMER can decide to import fossil fuels and biofuels from other region, in first instance based on differences in production and transportation costs. In addition, various forms of trade constraints exist. First of all, import and export constraints per region can simply prevent trade, even if costs consideration would indicate trade to be an attractive option. Secondly, region can favor domestic production by means of economic subsidies. Finally, a matrix between the different regions exist that can make trade between two specific regions less attractive. This matrix can first of all incorporate certain geographical difficulties for trade (e.g. the mountain ranges), but can also be used to introduce regional blocks
Transport costs	The trade between regions is among other a function of transport costs. Transport costs on their turn are function of a regional distance matrix and transport costs per kilometer. The latter are an exogenously set model input

Appendix D. Scenario results

Main indicators for the A1 scenario for the three European regions (former USSR including Asian part)

	1971	1990	1995	2010	2030	2050	2075	2100
OECD Europe (A1)								
Secondary energy use (PJ)	30315	37304	38771	49197	65883	77415	86320	88412
Electricity use (PJe)	3772	7122	7812	10769	16869	23549	30072	34390
Fraction fossil fuel input for electricity generation (%)	87	74	72	72	66	57	47	31
User costs (US\$ 1995/GJ)	17.1	15.5	15.5	15.8	17.3	18.2	18.7	18.9
Primary fuel consumption (PJ)	42418	53413	55715	68807	86213	98257	105884	103677
Crude oil price	3.1	3.3	3.2	3.6	5.1	7.3	10.0	11.8
Ratio energy production/consumption	0.4	0.6	0.6	0.5	0.6	0.5	0.6	0.6
CO ₂ emissions	813	933	951	1147	1278	1203	1180	967
East Europe (A1)								
Secondary energy use (PJ)	6528	7515	7190	13322	21705	21308	19941	17378
Electricity use (PJe)	706	1229	1152	2652	5655	6436	6965	6936
Fraction fossil fuel input for electricity generation (%)	97	92	90	90	82	57	40	19
User costs (US\$ 1995/GJ)	3.2	5.6	5.8	7.0	9.8	12.5	14.2	15.8
Primary fuel consumption (PJ)	9152	10729	10728	19543	29709	26497	23748	19530
Crude oil price	3.5	3.8	3.8	3.6	5.2	7.4	10.1	12.2
Ratio energy production/consumption	0.8	0.8	0.7	0.5	0.4	0.6	0.9	1.1
CO ₂ emissions	197	221	211	376	497	342	259	166
Former USSR (A1)								
Secondary energy use (PJ)	26088	40702	28573	39883	58695	63812	67490	63603
Electricity use (PJe)	2279	4572	3335	5594	10665	15014	21202	24925
Fraction fossil fuel input for electricity generation (%)	95	93	90	90	87	68	48	21
User costs (US\$ 1995/GJ)	0.9	2.5	2.2	3.1	5.4	9.4	11.8	14.5
Primary fuel consumption (PJ)	33335	53385	37228	49548	72752	76253	78182	69551
Crude oil price	3.0	2.9	2.8	2.9	4.3	7.1	10.4	12.2
Ratio energy production/consumption	1.1	1.2	1.3	1.3	1.8	3.3	4.2	3.0
CO ₂ emissions	636	916	624	815	1190	1075	953	645

Main indicators for the B1 scenario for the three European regions

	1971	1990	1995	2010	2030	2050	2075	2100
OECD Europe (B1)								
Secondary energy use (PJ)	30315	37303	38786	46467	48638	45443	39602	34975
Electricity use (PJe)	3772	7122	7815	10438	12857	14664	14638	14517
Fraction fossil fuel input for electricity generation (%)	87	74	72	73	65	55	44	31
User costs (US\$ 1995/GJ)	17.1	15.5	15.5	16.9	20.5	22.9	24.4	25.1
Primary fuel consumption (PJ)	42418	53413	55738	65768	63981	57342	48665	41468
Crude oil price	3.1	3.3	3.2	3.6	4.8	6.0	7.8	8.6
Ratio energy production/consumption	0.4	0.6	0.6	0.5	0.5	0.6	0.7	0.7
CO ₂ emissions	813	933	952	1094	913	682	455	314

Appendix D. (Continued)

	1971	1990	1995	2010	2030	2050	2075	2100
East Europe (B1)								
Secondary energy use (PJ)	6528	7515	7193	9429	13215	12939	10398	7802
Electricity use (PJe)	706	1229	1153	1873	3655	4332	4022	3418
Fraction fossil fuel input for electricity generation (%)	97	92	90	89	86	65	50	32
User costs (US\$ 1995/GJ)	3.2	5.6	5.8	7.7	12.1	17.8	20.1	22.0
Primary fuel consumption (PJ)	9152	10729	10733	13731	18660	16578	12889	9222
Crude oil price	3.5	3.8	3.8	3.7	4.9	6.1	7.9	8.7
Ratio energy production/consumption	0.8	0.8	0.7	0.5	0.4	0.5	1.1	1.3
CO ₂ emissions	197	221	212	260	308	221	134	76
Former USSR (B1)								
Secondary energy use (PJ)	26088	40702	28580	32424	38431	36979	32257	26281
Electricity use (PJe)	2279	4572	3336	4579	7480	9762	10897	10805
Fraction fossil fuel input for electricity generation (%)	95	93	90	88	86	71	52	30
User costs (US\$ 1995/GJ)	0.9	2.5	2.2	3.6	7.0	13.7	16.9	19.6
Primary fuel consumption (PJ)	33335	53385	37238	39852	47935	44901	38247	29711
Crude oil price	3.0	2.9	2.8	2.9	3.7	5.8	7.5	8.6
Ratio energy production/consumption	1.1	1.2	1.3	1.4	1.8	2.6	4.0	4.0
CO ₂ emissions	636	916	624	647	767	634	433	254

Main indicators for the A1-550 scenario for the three European regions

	1971	1990	1995	2010	2030	2050	2075	2100
OECD Europe (A1-550)								
Secondary energy use (PJ)	30315	37304	38771	48810	61750	71217	78686	81042
Electricity use (PJe)	3772	7122	7812	11001	17043	23424	29866	34080
Fraction fossil fuel input for electricity generation (%)	87	74	72	60	20	15	10	6
User costs (US\$ 1995/GJ)	17.1	15.5	15.5	20.6	25.0	28.0	30.1	29.9
Primary fuel consumption (PJ)	42418	53413	55715	65352	72024	81095	87297	88025
Crude oil price	3.1	3.3	3.2	3.6	5.1	6.2	8.0	9.6
Ratio energy production/consumption	0.4	0.6	0.6	0.6	0.6	0.6	0.7	0.7
CO ₂ emissions	813	933	951	1017	647	516	507	400
East Europe (A1-550)								
Secondary energy use (PJ)	6528	7515	7190	12760	19572	18789	17591	15603
Electricity use (PJe)	706	1229	1152	2640	5605	6413	6970	6939
Fraction fossil fuel input for electricity generation (%)	97	92	90	83	32	11	7	3
User costs (US\$ 1995/GJ)	3.2	5.6	5.8	11.3	17.1	23.3	27.2	29.2
Primary fuel consumption (PJ)	9152	10729	10728	17884	22817	20736	19149	16687
Crude oil price	3.5	3.8	3.8	3.9	5.2	6.2	8.1	9.8
Ratio energy production/consumption	0.8	0.8	0.7	0.4	0.5	0.6	0.9	1.0
CO ₂ emissions	197	221	211	313	231	137	111	77

Appendix D. (Continued)

	1971	1990	1995	2010	2030	2050	2075	2100
Former USSR (A1-550)								
Secondary energy use (PJ)	26088	40702	28573	38878	52702	54428	57749	56317
Electricity use (PJe)	2279	4572	3335	5619	10383	14791	20976	24715
Fraction fossil fuel input for electricity generation (%)	95	93	90	89	48	20	15	7
User costs (US\$ 1995/GJ)	0.9	2.5	2.2	5.0	12.2	21.3	26.0	27.8
Primary fuel consumption (PJ)	33335	53385	37228	48659	59744	59223	62525	59872
Crude oil price	3.0	2.9	2.8	2.9	4.0	5.9	8.0	9.5
Ratio energy production/consumption	1.1	1.2	1.3	1.3	1.8	2.7	3.7	3.5
CO ₂ emissions	636	916	624	760	626	469	432	310
Sum (A1-550)								
Secondary energy use (PJ)	62932	85521	74534	100448	134024	144434	154025	152962
Electricity use (PJe)	6758	12923	12300	19259	33031	44628	57813	65735
Fraction fossil fuel input for electricity generation (%)	92	86	82	76	33	16	12	6
User costs (US\$ 1995/GJ)	8.9	8.4	9.5	13.4	18.8	24.9	28.2	29.0
Primary fuel consumption (PJ)	84906	117527	103672	131895	154585	161054	168971	164584
Crude oil price	3.1	3.1	3.1	3.4	4.7	6.1	8.0	9.6
Ratio energy production/consumption	0.8	0.9	0.9	0.8	1.0	1.4	1.8	1.7
CO ₂ emissions	1646	2069	1787	2091	1504	1122	1050	787

Main indicators for the B1–450 scenario for the three European regions

	1971	1990	1995	2010	2030	2050	2075	2100
OECD Europe (B1-450)								
Secondary energy use (PJ)	30315	37303	38786	45689	46708	43882	38362	34097
Electricity use (PJe)	3772.345	7122	7815	10316	12613	14466	14463	14336
Fraction fossil fuel input for electricity generation (%)	87	74	72	68	31	20	11	7
User costs (US\$ 1995/GJ)	17.1	15.5	15.5	18.6	24.2	25.9	27.4	27.6
Primary fuel consumption (PJ)	42418	53413	55738	63555	56370	50836	43398	37943
Crude oil price	3.1	3.3	3.2	3.6	4.8	5.7	6.6	7.2
Ratio energy production/consumption	0.4	0.6	0.6	0.5	0.6	0.6	0.7	0.7
CO ₂ emissions	813	933	952	1017	586	348	219	146
East Europe (B1-450)								
Secondary energy use (PJ)	6528	7515	7193	9190	12257	12166	9902	7514
Electricity use (PJe)	706	1229	1153	1847	3500	4265	4009	3404
Fraction fossil fuel input for electricity generation (%)	97	92	90	86	62	24	13	7
User costs (US\$ 1995/GJ)	3.2	5.6	5.8	9.4	16.5	21.5	23.4	25.0
Primary fuel consumption (PJ)	9152	10729	10733	13119	15745	13971	11171	8308
Crude oil price	3.5	3.8	3.8	3.7	4.9	5.7	6.7	7.3
Ratio energy production/consumption	0.8	0.8	0.7	0.4	0.5	0.6	0.8	1.0
CO ₂ emissions	197	221	212	235	197	105	62	35

Appendix D. (Continued)

	1971	1990	1995	2010	2030	2050	2075	2100
Former USSR (B1-450)								
Secondary energy use (PJ)	26088	40702	28580	31878	35706	34020	30137	25035
Electricity use (PJe)	2279	4572	3336	4560	7237	9439	10699	10612
Fraction fossil fuel input for electricity generation (%)	95	93	90	88	75	28	13	4
User costs (US\$ 1995/GJ)	0.9	2.5	2.2	4.3	10.4	18.2	21.4	23.3
Primary fuel consumption (PJ)	33335	53385	37238	39024	43352	36825	32299	26467
Crude oil price	3.0	2.9	2.8	2.9	3.6	5.3	6.4	7.0
Ratio energy production/consumption	1.1	1.2	1.3	1.4	1.7	2.4	3.2	3.3
CO ₂ emissions	636	916	624	608	592	323	208	126

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